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The Global Turbidity Current Pump and Its Implications for Organic Carbon Cycling

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Keywords

turbidity current, submarine fan, organic carbon cycling, terrestrial organic carbon, marine organic carbon, burial efficiency

Abstract

Submarine turbidity currents form the largest sediment accumulations on Earth, raising the question of their role in global carbon cycles. It was previously inferred that terrestrial organic carbon was primarily incinerated on shelves and that most turbidity current systems are presently inactive. Turbidity currents were thus not considered in global carbon cycles, and the burial efficiency of global terrestrial organic carbon was considered low to moderate (∼10–44%). However, recent work has shown that burial of terrestrial organic carbon by turbidity currents is highly efficient (>60–100%) in a range of settings and that flows occur more frequently than once thought, although they were far more active at sea-level lowstands. This leads to revised global estimates for mass flux (∼62–90 Mt C/year) and burial efficiency (∼31–45%) of terrestrial organic carbon in marine sediments. Greatly increased burial fluxes during sea-level lowstands are also likely underestimated; thus, organic carbon cycling by turbidity currents could play a role in long-term changes in atmospheric CO_2 and climate.

INTRODUCTION

Seafloor avalanches of sediment called turbidity currents form the largest sediment accumulations (termed submarine fans), deepest canyons, and longest channel systems on our planet (Talling et al. 2015). Turbidity currents have a wide range of runouts and speeds, but some flows can travel for hundreds or even thousands of kilometers (Piper et al. 1999, Talling et al. 2007), making them the longest sediment flows on Earth (Talling et al. 2022). Some flows sustain speeds of 5–8 m/s for more than 1,000 km (Talling et al. 2022) or reach speeds of ~20 m/s (Piper et al. 1999, Gavey et al. 2017). Only rivers carry similar amounts of sediment over such large areas (Milliman & Farnsworth 2011, Syvitski et al. 2022), but sediment transport by turbidity currents is far more episodic, and a single event can transport more sediment than the combined annual flux from all rivers (Talling et al. 2007). For example, a turbidity current in the northeast Atlantic in 1929 carried ~25 times the modern global riverine annual sediment flux for ~800 km (Piper et al. 1999, Syvitski et al. 2022) (**Supplemental Figure 1**). The mass of sediment carried by turbidity currents thus rivals the mass carried by any other global sediment transfer system (or pump), including rivers, glaciers, and vertical settling of sediment from the surface ocean (**Figure 1*a***; **Supplemental Figure 1**).

Supplemental Material >

As turbidity currents are one of the most important sediment transfer processes (pumps) on Earth (**Figure 1*a***; **Supplemental Figure 1**), this raises the question of their importance for the transfer and burial of organic carbon (OC) in that sediment. Indeed, turbidity currents can produce rapid sediment accumulation (e.g., 0.5–20 cm/year; Dennielou et al. 2017), which favors efficient OC burial. Efficient burial of OC within marine sediment may play a role in atmospheric CO_2 drawdown, impacting global climate over timescales of thousands of years or longer (Hilton & West 2020). However, many influential analyses of global carbon burial in the oceans have neglected the role of turbidity currents (Berner 1982, 1989; Hedges et al. 1997; Burdige 2007; Blair & Aller 2012), assuming that terrestrial OC supplied by rivers was buried almost exclusively within deltas or other parts of continental shelves (**Table 1**). These past studies have also inferred that most terrestrial OC was remineralized on river-dominated continental shelves, with extensive mobile-mud belts, as occurs offshore from the Amazon River (Aller 1998, Nittrouer et al. 2021), such that the present-day global burial efficiency of terrestrial OC in marine sediments was relatively low (10–44%; **Table 1**). In addition, previous models (e.g., sequence-stratigraphic models; Posamentier & Kolla 2003) have concluded that present-day turbidity current systems are mainly inactive (**Figure 2*c***), as global sea-level rise during the Late Holocene flooded continental shelves. Sea-level rise detached the majority of submarine canyon heads from river mouths; only ~180 of ~9,500 canyon heads currently extend to river mouths (Harris et al. 2014, Bernhardt & Schwanghart 2021).

There is growing recognition that a wide range of turbidity current systems have remained active in modern times (**Figure 2*d***) and that these systems include not only the small number where river mouths still connect directly to canyon heads (Khripounoff et al. 2012, Liu et al. 2012, Bonneau et al. 2014, Azpiroz-Zabala et al. 2017, Talling et al. 2022) but also some that are fed by longshore drift (Covault & Graham 2010, Paull et al. 2018) and some where canyons are separated from river mouths by wider shelves (Rogers & Goodbred 2010, Heijnen et al. 2022b). At these locations, burial of terrestrial OC can be highly efficient (Galy et al. 2007, Kao et al. 2014,

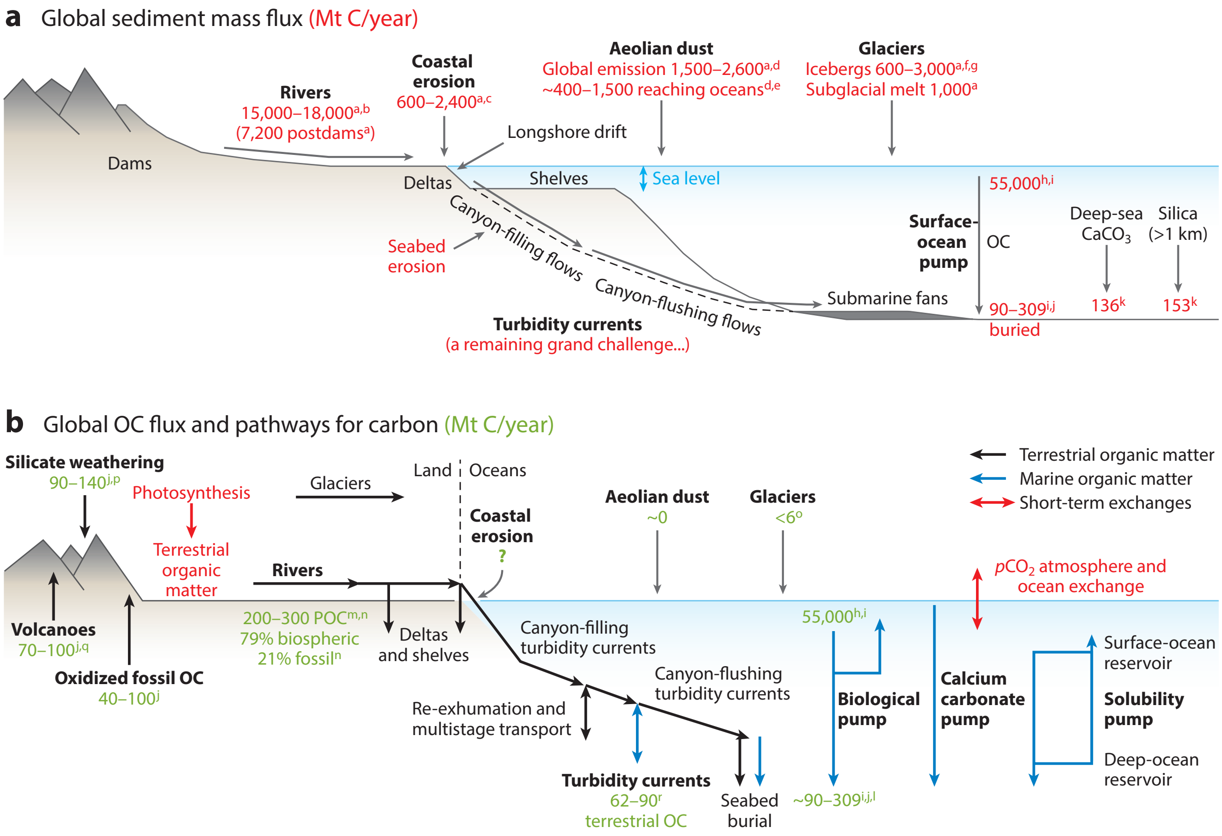


Figure 1

Summary of different global sediment and OC pumps, including the turbidity current pump. (*a*) Global sediment mass fluxes (in *red*). Values are from [a]Syvitski et al. (2022), [b]Milliman & Farnsworth (2011), [c]Regard et al. (2022), [d]Jickells et al. (2005), [e]Maher et al. (2010), [f]Raiswell et al. (2008), [g]Hasholt et al. (2022), [h]Burdige (2005), [i]Burdige (2007), [j]Hilton & West (2020), and [k]Hayes et al. (2021); values from Hayes et al. (2021) are for water depths greater than 1 km. Quantifying the global sediment flux carried by turbidity currents is a remaining grand challenge. (*b*) Global OC mass fluxes (in *green*). Values are from [h]Burdige (2005), [i]Burdige (2007), [j]Hilton & West (2020), [l]Cartapanis et al. (2018), [m]Li et al. (2022), [n]Galy et al. (2015), [o]Wadham et al. (2019), [p]Gaillardet et al. (1999), [q]Plank & Manning (2019), and [r]this review. This diagram summarizes global pathways of both terrestrial (*black*) and marine (*blue*) OC. Abbreviations: OC, organic carbon; POC, particulate organic carbon.

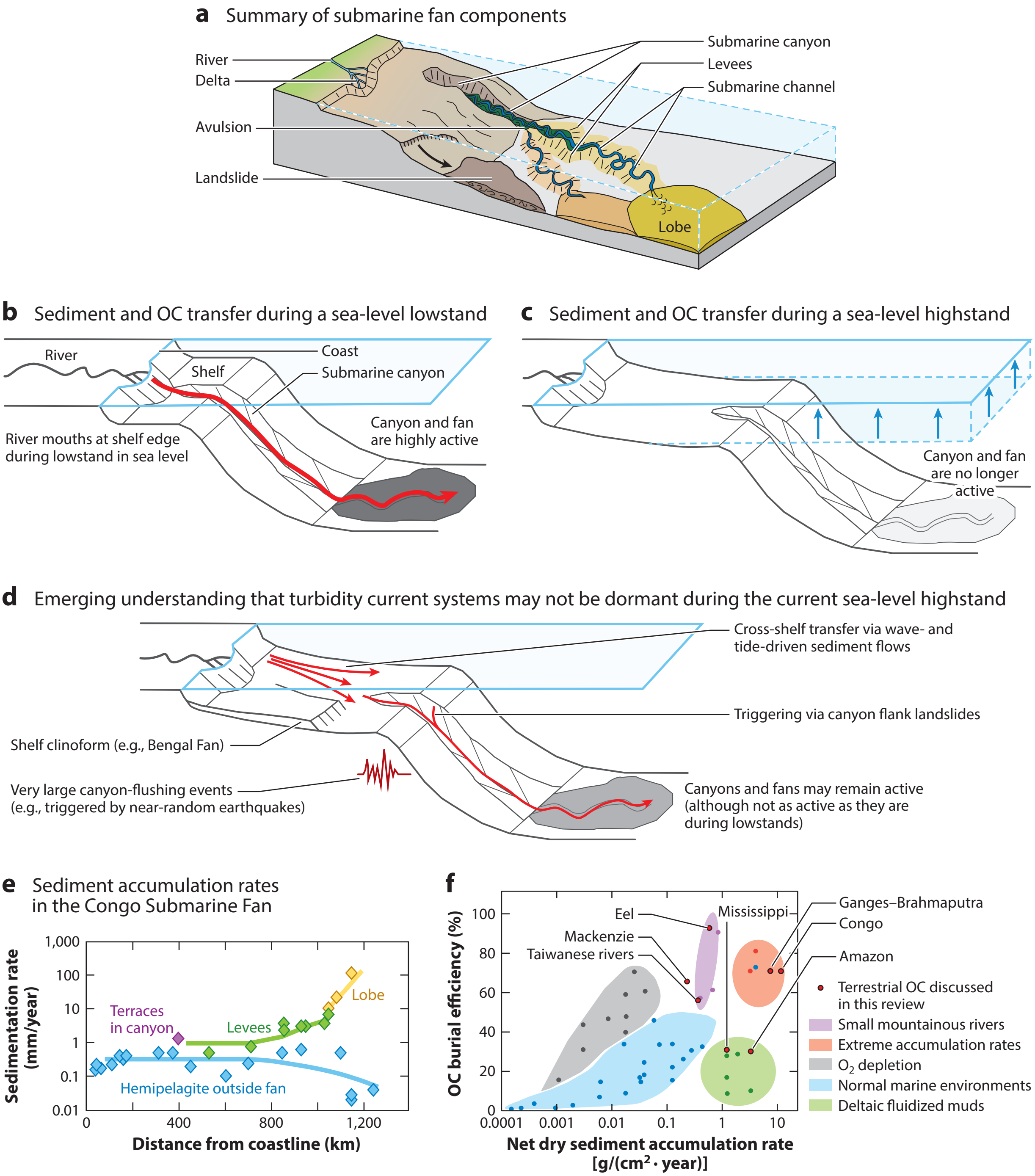
Sampere et al. 2008, Bao et al. 2015, Baudin et al. 2020). For example, the Bengal Submarine Fan offshore from the Ganges and Brahmaputra Rivers is the largest sediment accumulation on Earth, and these two rivers alone account for 8–10% of the terrestrial OC transferred by rivers to oceans (Galy et al. 2007, Milliman & Farnsworth 2011). An analysis of seabed cores and comparisons with riverine sediment samples showed negligible loss of terrestrial OC in the deep-sea fan (i.e., ~100% burial efficiency) (Galy et al. 2007). Other studies also concluded that terrestrial OC burial by turbidity currents can be highly efficient in fjords (Smith et al. 2015, Bianchi et al. 2020, Hage et al. 2022) and in turbidity current systems fed by small mountainous rivers, such as offshore Taiwan (Kao et al. 2014, Bao et al. 2015). Efficient OC burial in these systems is linked to unusually rapid sediment accumulation within turbidity current deposits (turbidites), resulting in a low O_2 penetration depth (a few centimeters) in seabed sediment (Galy et al. 2007; Rabouille et al. 2017, 2019).

Table 1 Estimates of the global amount and efficiency of OC burial in seabed sediments at the present-day interglacial highstand and glacial lowstand in sea level

Study	Terrestrial total POC supplied by rivers (Mt/year)	Terrestrial total POC global burial efficiency in marine sediment	Terrestrial total POC global burial flux in marine sediment (Mt/year)	Total POC (terrestrial and marine OC) burial flux in marine sediments (Mt/year)
Present-day interglacial highstand in sea level				
Berner 1982, 1989				∼130
Hedges et al. 1997		10–30%		∼160
Burdige 2005, 2007	170–200	14–30%	40–80	∼170[a]
Schlünz & Schneider 2000	460 (for both POC and DOC)	10%	46	
Blair & Aller 2012	170–200	20–44%		
Galy et al. 2015	200 (157 biospheric)			
Hilton & West 2020	200–300[b]	10–30%	40–80	∼170[a]
This review	200 (157 biospheric)	31–45% (28–51% biospheric)	62–90[c] (44–80 biospheric[c])	152–220[a]
Glacial lowstand in sea level				
Cartapanis et al. 2016		50%	27 (only >1-km water depth)	
This review		60–80% (60–80% biospheric)	130–175[d] (103–138 biospheric)	220–305[d,e]

Abbreviations: DOC, dissolved organic carbon; OC, organic carbon; POC, particulate organic carbon; TOC, total organic carbon.
[a]Assumes that the burial flux of marine OC remains at 90–130 Mt/year (Hilton & West 2020), but note that Burdige (2007) cites a significantly higher value of ∼310 Mt/year for the present-day flux of marine OC that is buried.
[b]Also based on Li et al. (2022).
[c]Assumes a global TOC flux of 200 Mt/year and a biospheric flux that is 79% of 200 Mt/year (i.e., 157 Mt/year).
[d]Includes ∼10–15 Mt/year of terrestrial OC buried globally within glacial trough-mouth fans and assumes that neither the global supply of terrestrial OC nor the fraction that is biospheric changed between the glacial lowstand and the present-day highstand.
[e]To allow comparison, assumes that the burial of marine OC (∼90–130 Mt/year) did not change between the glacial lowstand and the present-day highstand.

It was once thought that turbidity currents were impractical to measure in action, due to their ability to damage sensors in their path or flush them into the deep sea (Kneller & Buckee 2002). However, over the last decade or so, turbidity currents have been measured in detail at a series of locations worldwide in a variety of settings (e.g., Khripounoff et al. 2012, Hughes Clarke 2016, Azpiroz-Zabala et al. 2017, Paull et al. 2018, Hill & Lintern 2022, Talling et al. 2022). Direct flow monitoring consistently found that turbidity currents were much more active than previously inferred by many models (e.g., sequence-stratigraphic models) (Posamentier & Kolla 2003). For example, multiple powerful (up to 6 m/s) turbidity currents occurred over ∼1 year in Whittard Canyon even though this canyon's head is located >300 km from the coast (Heijnen et al. 2022b). Turbidity currents occurred even in canyons fed by rocky shorelines that lack obvious sediment sources (Normandeau et al. 2020). Powerful flows also occurred on open slopes outside submarine canyons (Hill & Lintern 2022), and more than 100 flows occurred on a Canadian fjord-head delta in ∼3 months (Clare et al. 2016), while flows occurred for 30% of the time in the river-connected Congo Submarine Canyon (Azpiroz-Zabala et al. 2017). This direct flow monitoring has been combined with sediment cores and time-lapse seabed mapping that constrains sediment mass fluxes to provide important new insights into how turbidity currents transfer and bury OC (Hage et al. 2020, 2022; Maier et al. 2019). For example, monitoring of turbidity currents that originated in the Congo River estuary showed how turbidity currents can efficiently transfer



(*Caption appears on following page*)

Figure 2 (*Figure appears on preceding page*)

Controls on the efficiency of sediment and OC transfer or burial efficiency within submarine fans. (*a*) Basic components of a submarine fan. (*b*) Sediment and OC transfer during a sea-level lowstand. This transfer is highly efficient during a lowstand because almost all river mouths connect to canyon heads. (*c*) Sediment and OC transfer during a sea-level highstand. Past sequence stratigraphic models assumed that most submarine fans are dormant during sea-level highstands, as most river mouths are separated from canyon heads (e.g., Posamentier & Kolla 2003). (*d*) Emerging understanding that turbidity current systems in many locations may not be dormant during sea-level highstands, as sediment may reach some canyon heads. (*e*) Sediment accumulation rates in different components of the Congo Submarine Fan. Data are from Baudin et al. (2020). (*f*) Relationship between sediment accumulation rates and OC burial efficiencies in different settings, including for burial of terrestrial OC in submarine fans at sites discussed in this review (*red dots*). Abbreviation: OC, organic carbon. Panel *f* adapted with permission from Blair & Aller (2012).

terrestrial OC to the deep sea (Talling et al. 2022). Turbidity currents that traveled for >1,100 km were associated with major river floods but triggered weeks to months later at spring tides. They flushed a large sediment mass, equivalent to 19–35% of the global annual river sediment flux, down just one submarine canyon in a single year (Talling et al. 2022). Monitoring has also shown how sediment and OC transfer to the deep sea occurs in multiple stages, affecting residence times and loss of OC (Hage et al. 2022, Heijnen et al. 2022a, Talling et al. 2022).

These new developments mean that it is timely to assess the role of turbidity currents in global cycling of OC in the present day, including evaluating whether previous estimates of modern global terrestrial OC burial in marine sediments of ~40–80 Mt C/year (Burdige 2005, 2007) need to be revisited (**Table 1**) and how turbidity current system types affect carbon cycling. OC burial efficiency by turbidity currents would have been far higher during glacial times (Cartapanis et al. 2016), when lower global sea levels ensured that almost all rivers connected directly to submarine canyon heads (Harris et al. 2014). This review therefore also briefly assesses whether previous work (Cartapanis et al. 2016, 2018) may have underestimated glacial–interglacial variability in global terrestrial OC burial by turbidity currents (e.g., Cui et al. 2022).

The overarching aim of this review is to assess the role of turbidity currents in OC cycling, especially that of terrestrial OC. To do this, it addresses several specific questions: What sources of OC do turbidity currents contain, and what controls their fate? Do turbidity currents segregate different OC types en route (i.e., is there a leaky pipeline)? How does OC cycling by turbidity currents work in different types of settings, and what are the main controls on burial efficiency? Do we need to revise global estimates for the amount and efficiency of terrestrial OC burial in marine sediments? And finally, how do glacial–interglacial sea-level cycles affect OC burial efficiency by turbidity currents within marine sediments, and have changes in global burial efficiency previously been underestimated?

BACKGROUND

How Turbidity Currents Are Part of Wider Global Carbon Cycles

The global carbon cycle involves the exchange of carbon between the major reservoirs at Earth's surface (the atmosphere, terrestrial and marine biosphere, and oceans) and storage in sedimentary rocks and the deeper lithosphere of the Earth (Sundquist & Visser 2004, Bianchi 2011, Hilton & West 2020) (**Figure 1*b***). CO_2 is a focus of research because of its role as a greenhouse gas that helps set Earth's radiative energy balance and surface climate. Over short timescales ($<10^1$ to 10^3 years), the natural (nonanthropogenic) carbon cycle is dominated by exchanges between the atmosphere and living biosphere (e.g., via photosynthesis on land or in upper oceans) and CO_2 exchange between the ocean and atmosphere (Sundquist 1993). Over longer timescales (10^4 to $>10^6$ years), inputs of CO_2 from the solid Earth (Plank & Manning 2019) and additional sources of CO_2 from oxidative weathering of rock OC and sulfide minerals (Torres et al. 2014, Hilton & West 2020) are removed from the surface reservoirs via silicate mineral weathering and carbonate mineral formation (Ebelmen 1845, Galvez & Gaillardet 2012) as well as through long-term OC burial in sediments (Berner 1982). Marine sediments represent the longest (10^4 to $>10^6$ years) store of OC, which is roughly equally marine and terrestrial in origin based on modern-day estimates (Schlünz & Schneider 2000; Burdige 2005, 2007). Sediment transport processes play a central role in this geological carbon cycle because they affect sedimentation rates, which are a first-order control of OC burial efficiency (Berner 1982). These transport processes also affect the delivery of terrestrial OC to the ocean by rivers, as well as the subsequent movement of OC across the shelf and into the deep sea (Galy et al. 2015, Hilton 2017).

In this review, we focus on the specific role of turbidity currents as a pathway for OC transfer. Primarily, this pathway transfers OC between the coast and the deep sea, although depending on the timing and trigger of turbidity currents, it can directly couple terrestrial ecosystems to the deep ocean in river floodwaters (Hilton et al. 2008, Talling et al. 2022). In terms of net CO_2 transfers, sediment transfer by turbidity currents can aid the long-term preservation of terrestrial and marine OC in sedimentary deposits. In broader terms, any remineralization of OC (i.e., the processes of organic matter decomposition by heterotrophic or chemotrophic mechanisms) within turbidity current deposits can release inorganic carbon into the deep-sea dissolved inorganic carbon reservoir, which already holds a very large mass of carbon (Dunne et al. 2007, Houghton 2007) (**Figure 1*b***). It may take thousands of years for relatively small fractional changes in this deep-sea inorganic carbon reservoir to exchange with the surface ocean and other reservoirs and thus affect atmospheric CO_2 levels (Gruber et al. 2023). Transfer of more oxygen-rich waters by turbidity currents to the deeper ocean may also affect the rate at which OC is cycled through benthic ecosystems (Quadfasel et al. 1990, Bianchi et al. 2016). However, given the fluxes involved, it is unlikely that the turbidity current pump rivals the well-studied ocean carbon pumps that help control CO_2 concentrations in the atmosphere over short timescales (10^3–10^4 years). Instead, based on our current understanding of the carbon fluxes involved in sediment-driven flows, changes in OC burial and remineralization associated with turbidite deposition are likely to affect atmospheric CO_2 and climate over millennial or longer (geological) timescales (Galy et al. 2007).

Burial efficiency is a useful metric to describe the ratio of carbon buried to the supply of carbon to the burial site. OC burial efficiency within turbidity current deposits, and more generally on the seabed, is affected by a series of factors (Burdige 2005, 2007; Blair & Aller 2012; Arndt et al. 2013; Shang 2023). First, the source of OC is one important control on the rate of OC decomposition, which may decay quasi-exponentially over time (Blair & Aller 2012, Bianchi et al. 2018, Eglinton et al. 2021). Marine OC is typically remineralized more quickly than terrestrial OC, which reflects its inherent reactivity and bioavailability for heterotrophs (Burdige 2007, Bianchi 2011, Blair & Aller 2012, Regnier et al. 2022). The source of OC is also critical as a food resource to the benthos, with unstable or labile OC promoting much greater benthic biomass than does more stable refractory terrestrial OC (Amaro et al. 2016, Leduc et al. 2020).

A combination of sediment accumulation rate and the oxygen levels in that sediment affects a second important parameter, the integrated oxygen-exposure time (Hartnett et al. 1998, Blair & Aller 2012, Bianchi et al. 2016). Faster sediment accumulation and lower oxygen levels promote more efficient carbon burial. Turbidity currents can produce unusually rapid sedimentation (**Figure 2*e*,*f***). For example, accumulation of sediment rich in terrestrial OC occurs at 0.5–20 cm/year across the ~4,800-m-deep lobe at the end of the Congo submarine system (Dennielou et al. 2017) (**Figure 2*e***) and at 5–50 cm/year in the canyon head on the Bengal Fan (Rogers & Goodbred 2010) (**Figure 2*f***). Remineralization of this rapidly accumulating organic matter may lead to anoxic conditions within seabed sediments that also favor higher efficiency of OC burial (Blair & Aller 2012; Arndt et al. 2013; Rabouille et al. 2017, 2019; Middelburg 2018) (**Figure 3**).

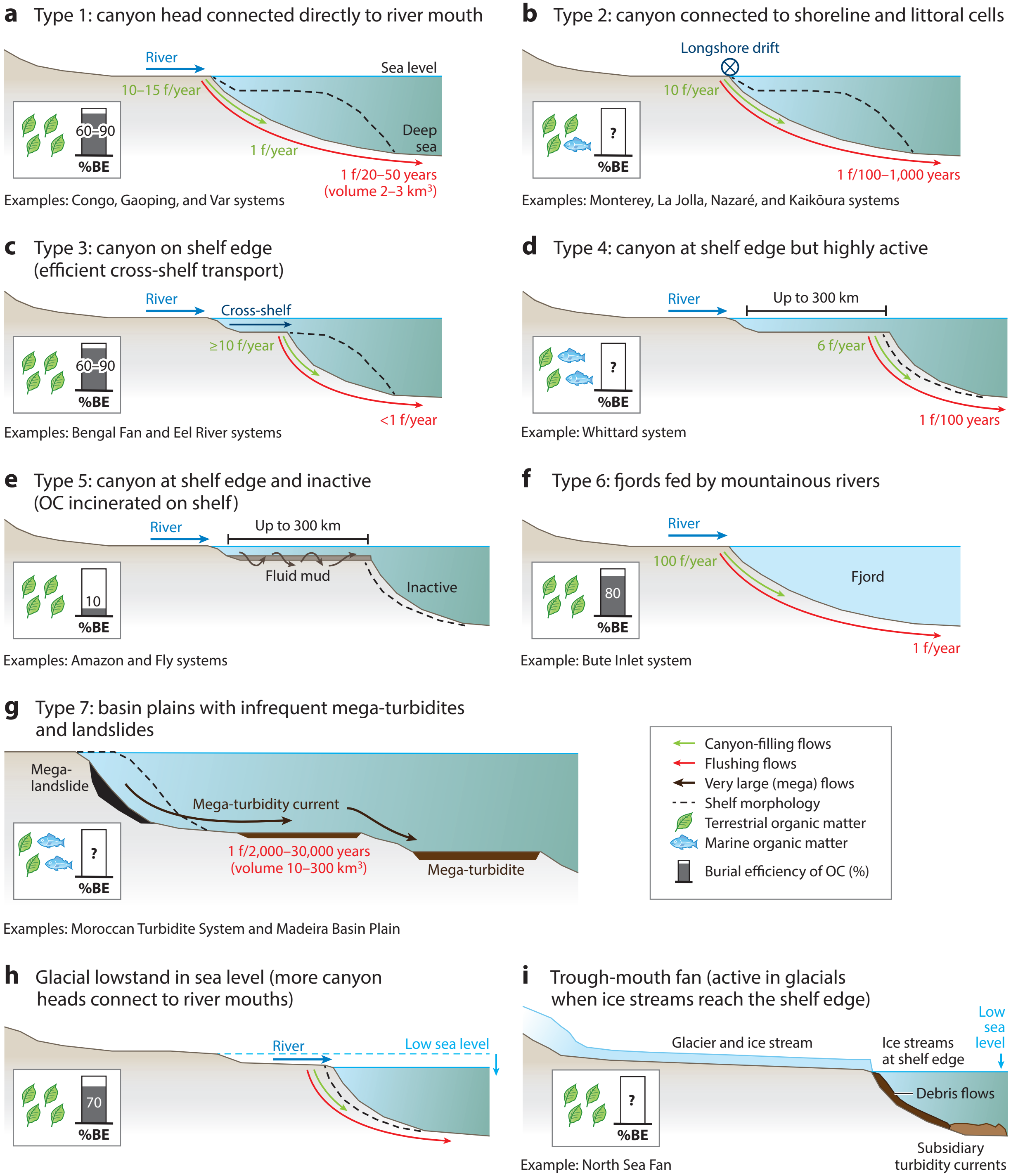


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Figure 3 (*Figure appears on preceding page*)

Sediment and OC transfer by different types of turbidity current system. The average recurrence intervals between flows are shown (where, e.g., 1 f/20–50 years denotes that one flow occurs on average every 20–50 years), followed in some cases by the approximate flow volume. (*a*) Type 1: submarine canyon head that connects directly to a river mouth. (*b*) Type 2: submarine canyon that connects to the shore and is fed by longshore drift. (*c*) Type 3: submarine canyon that only partially indents the shelf, but sediment still reaches it from rivers. (*d*) Type 4: submarine canyon that is restricted to the shelf edge but is still highly active. (*e*) Type 5: submarine canyon that is at the shelf edge and assumed to be inactive. (*f*) Type 6: fjords where a river mouth feeds directly into deep water. (*g*) Type 7: mega-landslides and abyssal plains with infrequent but very large turbidity currents. (*h*) Glacial lowstands when all rivers connect to canyon heads, as in type 1. (*i*) Trough-mouth fan active during a glacial lowstand. Abbreviation: OC, organic carbon.

Another important factor controlling carbon burial is organo-mineral associations, such as sorption to clays and complexation with iron and/or manganese oxides (Lalonde et al. 2012, Keil & Mayer 2014, Blattmann et al. 2019, Hemingway et al. 2019). Consequently, hydrodynamic sorting during transport is key in controlling the OC composition and the distances that organo-mineral materials from riverine and/or resuspended shelf sediments are transported to deeper waters (Prahl et al. 1994, Keil et al. 1997, Bianchi et al. 2002). In some cases, much of the terrestrially derived particulate OC from rivers, which is largely in the organo-mineral form (Bauer et al. 2013, Regnier et al. 2022), can be replaced by marine OC that sorbs to clay particles as it moves across the shelf (Prahl et al. 1994, Keil et al. 1997).

Further Background on Turbidity Current Systems

Turbidity currents are mixtures of sediment and water that move downslope due to the density contrast between this mixture and surrounding water (Kuenen & Migliorini 1950, Talling et al. 2012). These sediment flows are generated in many ways, such as by disintegration of landslides that mix with seawater, which produce the largest-volume turbidity currents (Piper et al. 1999; Talling 2014; Talling et al. 2007, 2014). Submarine landslides are sometimes orders of magnitude larger than terrestrial landslides (Talling et al. 2014). The 1929 turbidity current in the northeast Atlantic was larger than any terrestrial landslide in the last 350,000 years (Piper et al. 1999, Korup et al. 2007) (**Supplemental Figure 1**). Seabed failures of different sizes can be triggered in many ways, including by earthquakes, storm-wave loading, and progradation of delta lips or canyon-head lips (Talling et al. 2014), or sometimes even without a major external trigger (Bailey et al. 2021). Turbidity currents are also generated via river plumes. On rare occasions, and for just a few rivers, this river plume can have sufficient suspended sediment to be denser than seawater and plunge to move along the seabed as a hyperpycnal flow (Mulder et al. 2003, Kao et al. 2010, Liu et al. 2012). Much more often, turbidity currents are initiated by sediment settling from surface river plumes that are less dense than seawater, which occurs for rivers with a much wider range of sediment concentrations (Hage et al. 2019). Turbidity currents can be triggered by human activities such as seabed trawling, although these flows tend to be relatively small (Puig et al. 2012, Paradis et al. 2022).

Supplemental Material >

Turbidity currents typically occur for $<0.1\%$ of the time and last for hours or minutes (Hughes Clarke 2016, Paull et al. 2018, Hage et al. 2019, Pope et al. 2022), although flows in the upper Congo Canyon occur for 20–30% of the time and can last for a week (Azpiroz-Zabala et al. 2017, Simmons et al. 2020). Transfer of OC by turbidity currents is much more episodic than transfer by rivers that flow continuously (albeit with floods) or the steadier settling of OC from surface oceans. The magnitudes of turbidity currents are also extremely variable, ranging from very small flows traveling <1 km (Hughes Clarke 2016) to those carrying more sediment than the annual global riverine flux for ~1,000 km (Talling et al. 2007). Turbidity currents are separated into much larger events that erode and flush submarine canyons, which may occur every few decades to millennia, and smaller and more frequent flows that infill canyons (Allin et al. 2016, Talling et al. 2022).

Thus, OC is often buried initially by canyon-filling flows before being re-exhumed by infrequent canyon-flushing flows in a second stage of transport, during which OC may be partly remineralized and lost (Heijnen et al. 2020, 2022a; Hage et al. 2022; Talling et al. 2022).

Submarine fans (**Figure 2*a***) are built by turbidity currents and occur in locations worldwide (Normark et al. 1986, Covault 2011). Because of its different densities or sizes, OC may be hydrodynamically segregated within the flow as it moves across submarine fans, such that different components have variable accumulation rates and burial efficiencies (Stetten et al. 2015, McArthur et al. 2017). Submarine fans are typically divided into a deeply eroded canyon, which continues as a less deeply incised channel (Normark et al. 1986, Covault 2011) (**Figure 2*a***). Sediment overspill from the channel creates adjacent upraised levees, while sediment deposition at the end of the channel produces a lobe (Hodgson et al. 2022). Exceptionally flat (<0.05°) basin plains in the deep sea also trap sediment beyond these lobes (Talling et al. 2007, 2012).

Highly Mobile Mud Layers on the Shelf

Highly mobile layers of fluid mud play a key role in the transfer of sediment and OC across continental shelves from river mouths to submarine canyons on the shelf edge. These highly mobile muds are commonly found at the mouths of large river systems with high suspended loads, and they can be generated by resuspension of mud by wave-related or tidal currents (Kuehl et al. 1996, Aller 1998, Allison et al. 2007, Xu et al. 2015). For example, mobile muds off the Mississippi/Atchafalaya River systems were transported offshore to the Mississippi Canyon after the passage of a hurricane, with much of the OC derived from marine organic matter from nearshore in the highly productive Mississippi River plume (Bianchi et al. 2006, Sampere et al. 2008). These dynamic mud deposits can serve as incinerators of OC, due in part to their high oxygen content and availability in redox-sensitive elements (iron, manganese, and sulfur) (Aller & Blair 2006, Aller et al. 2010, Zhao et al. 2023). These mobile mud layers have also been hypothesized to trigger turbidity current events; for example, mud layers may drain into the tributary canyon head of the Congo Canyon during spring tides (Talling et al. 2022).

DISCUSSION

What Types of Organic Carbon Do Turbidity Currents Contain, and What Controls Those Types?

The total organic carbon (TOC) in turbidity current deposits can be relatively high (0.4–4%; e.g., Rabouille et al. 2017, 2019), exceeding global average values commonly assigned to deltas (0.75%) or continental shelf deposits (1.5%) (Berner 1982, 1989; Burdige 2005, 2007) and a global average TOC from rivers (1.1–1.6%) (Burdige 2005, 2007; Blair & Aller 2012) (**Table 1**). The fraction of terrestrial or marine OC in turbidity current systems broadly reflects how sediment is supplied. This includes sediment from river mouths, littoral cells, or cross-shelf transport for terrestrial OC and the productivity of overlying surface waters for marine OC (**Figure 3**).

The type and age of OC are also critically important for carbon cycling (Galy et al. 2007, Kao et al. 2014, Bao et al. 2015). Older forms of OC tend to be less easily remineralized (i.e., they tend be refractory), and marine OC is typically lost more rapidly (Blair & Aller 2012, Eglinton et al. 2021). Even more importantly, atmospheric CO_2 is drawn down via creation of fresh biospheric OC (OC_{bio}) via terrestrial or marine photosynthesis (Hilton & West 2020). Older and more refractory OC (petrogenic OC or OC_{petro}) that has been buried previously, and is now merely transported and reburied in another location, will not act to draw down atmospheric CO_2 (Galy et al. 2007) (**Figure 1*a***). As marine OC is rapidly remineralized, this fossil OC (OC_{petro}) is often mainly terrestrial. It has been estimated that rivers globally supply ∼157 Mt/year of OC_{bio} and

~43 Mt/year of fossil OC (OC_{petro}) (Galy et al. 2015) (**Table 1**). Previous work thus analyzed the fraction of OC_{bio} or OC_{petro} in turbidites (Galy et al. 2007, Kao et al. 2014, Hage et al. 2020). For example, it was once assumed that OC exported by small mountainous rivers was mainly fossil OC (Blair & Aller 2012), but other studies have shown that it can have a dominant OC_{bio} component (Kao et al. 2014), as is also the case in fjords (Hage et al. 2022).

Turbidity current systems are typically dominated by terrestrial OC, but in some locations organic matter is mainly marine, such as in the Kaikōura Canyon (Gibbs et al. 2020, Leduc et al. 2020). A large earthquake-triggered canyon-flushing turbidity current transferred ~8 Mt of mainly marine OC to the deep sea in 2016 (Mountjoy et al. 2018), as compared with the 90–130 Mt/year of marine OC buried globally, although canyon-flushing events in the Kaikōura Canyon may have recurrence intervals of ~140 years (Mountjoy et al. 2018).

Do Turbidity Currents Segregate Different Organic Carbon Types? Is There a Leaky Pipeline?

OC particles have lower densities than most sediment grains, as well as a wide range of sizes and shapes (Repasch et al. 2022, Schwab et al. 2022). Thus, different types of organic matter may be hydrodynamically sorted (Bianchi et al. 2002, Eglinton et al. 2021), ending up in different parts of submarine fans (e.g., McArthur et al. 2017) and thus being preferentially buried or remineralized within a leaky pipeline.

Finer-grained organic matter tends to be deposited within turbidite mud layers (Bouma T_E interval; Blair & Aller 2012, Talling et al. 2012). Mud makes up >70% of global sediment supplied by rivers to the oceans (Aplin et al. 1999), and many turbidity current systems are mud dominated, especially larger submarine fans fed by major rivers (Normark et al. 1986). As discussed above, fine mud is often key in preserving terrestrial organic matter because clays can shield particulate OC from degradation (Blair & Aller 2012, Keil & Mayer 2014, Blattmann et al. 2019, Hemingway et al. 2019). But in some settings, large amounts of fresh OC_{bio}, such as woody debris, can be deposited within turbidite sands (Saller et al. 2006, Kao et al. 2014, Lee et al. 2019, Hage et al. 2020). This woody material may be preferentially deposited within the finer upper levels of a sand layer (Bouma T_D division; Talling et al. 2012) or with the largest woody fragments found toward the sand layer's base (Bouma T_A and T_B intervals) and also within muddy sands deposited via debris flow (hybrid beds) (Haughton et al. 2003; Talling et al. 2004, 2012; Hussein et al. 2021). OC deposited in turbidite sands may be protected from oxidization by an overlying mud cap (Hage et al. 2020). Neglecting organic material in sand may then cause burial fluxes to be underestimated significantly, as has been shown in fjords (Hage et al. 2020). Standard methods to core the seabed tend not to penetrate sandy seabed deposits, which may lead to biases in global core data sets used for burial fluxes (e.g., Cartapanis et al. 2016, 2018; Li et al. 2023).

Submarine fan subenvironments contain different sediment grain sizes and accumulation rates, which can affect OC burial. Rapid sediment accumulation in lobes (**Figure 2*e***) favors more efficient OC burial, and lobes may be relatively sand rich (Hodgson et al. 2022), albeit with exceptions (Dennielou et al. 2017), while levees can also have high accumulation rates (**Figure 2*e***) but are mud dominated (Normark et al. 1986, Covault 2011, Baudin et al. 2020). Forensic tracking of different types of organic matter can show changes away from specific sources, such as particular rivers on the shelf (Gibbs et al. 2020). The shapes of an individual turbidite deposit may also affect OC burial efficiency. For example, very-large-volume turbidity currents may produce ponded mud deposits in basin plains that are tens of meters thick (Talling et al. 2007, 2012), with only the upper few tens of centimeters oxidized over thousands of years, such that the majority of underlying mud is protected (Thomson et al. 1987). Conversely, flows that spread sediment thinly and evenly will cause a greater fraction of OC to be remineralized, other factors being equal.

How Does Organic Carbon Cycling by Turbidity Currents Work in Different Types of Systems?

Here, we present a series of models that illustrate how OC transfer and burial work in different types of turbidity current system (**Figure 3**).

Type 1: submarine canyon head that connects directly to a river mouth. Very few (~180 of ~9,500) modern submarine canyons connect directly to river mouths (Harris et al. 2014, Bernhardt & Schwanghart 2021), but they include rivers with large sediment fluxes, such as the Congo, Gaoping, and Var systems (**Figure 3*a***). These submarine fans are dominated by terrestrial OC (>70 to ~100%), but the fraction of fresh or fossil terrestrial OC depends on the river type, with <2% fossil OC for the Congo River on a passive margin (Baudin et al. 2020). Small mountainous rivers may have higher fractions of fossil OC (e.g., 60–70%), with the OC supply also being highly episodic during floods (Kao et al. 2014, Bao et al. 2018). Turbidity currents are generated relatively frequently at river mouths in type 1 systems (Khripounoff et al. 2012, Liu et al. 2012, Azpiroz-Zabala et al. 2017, Talling et al. 2022). Organic matter may reside initially in canyon-floor deposits, maybe for years to decades, before being flushed into the deep sea by far larger flows (Allin et al. 2016, Mountjoy et al. 2018, Talling et al. 2022).

OC burial can be highly efficient (>70% to approaching 100%) in type 1 systems (Galy et al. 2007, Kao et al. 2014). For example, a mass balance that includes canyon-flushing events suggests that ~100% of Congo River sediment is transferred to the deep sea over 20–50-year timescales (Azpiroz-Zabala et al. 2017, Simmons et al. 2020, Talling et al. 2022) and deposited mainly beyond the channel mouth or on flanking levees (Talling et al. 2022). It is estimated that ~15% of OC is remineralized and recycled on the seabed in the Congo system, with a burial efficiency of ~85% on the lobe (Rabouille et al. 2017, Baudin et al. 2020), although the efficiency is lower if sediment is buried and re-exhumed multiple times. However, precise estimates of terrestrial OC burial efficiency are challenging, even in well-studied systems, because they require constraints on riverine inputs and tracking of all sediment through the deep-sea system. Baudin et al. (2020) concluded that 33–69% of the terrestrial OC supplied by the Congo River was buried in the Congo submarine fan, mainly in lobes and levees. However, approximately half of the OC supplied by the river was unaccounted for in their budget and may have been flushed beyond the lobe by very large flows, as in 2020 (Talling et al. 2022). Thus, burial efficiency is likely to be somewhat higher than 33–69%.

Type 2: submarine canyon that connects to the shore and is fed by longshore drift. Some of the ~180 modern canyons (Harris et al. 2014, Bernhardt & Schwanghart 2021) that extend close to the shoreline are fed mainly by littoral drift, with little or no direct connection to river mouths, yet show evidence of turbidity current events (**Figure 3*b***). Examples include Monterey Canyon (Paull et al. 2018, Maier et al. 2019) and Nazaré Canyon (Masson et al. 2010). Cores from Monterey Canyon are dominated by terrestrial OC, with annual sediment mass fluxes to the canyon (1–3 Mt/year) and TOC values (~0.5%) that are similar to those for nearby rivers (Paull et al. 2006, Maier et al. 2019, Bailey et al. 2021). This suggests there is efficient (>80–100%) burial of terrestrial OC from rivers in the upper canyon, despite an intervening period of time being reworked on the shelf. Much higher TOC values (~1.2–2.9%) occur in sediment traps in Monterey Canyon, with a large proportion of this OC being absent from seabed cores (Maier et al. 2019). This suggests that there is a large pool of easily resuspended and labile OC, likely primarily marine in origin, that is not buried. Nazaré Canyon has much higher TOC values (~2%) in seabed cores, with ~30% of OC in sediment trap samples estimated to be buried on the seabed (Masson et al. 2010). There may again be a pool of labile OC that is easily resuspended by internal tides and is trapped in the upper canyon and remineralized before burial, albeit a smaller fraction than within Monterey Canyon. In both locations, canyon-flushing flows occur every few hundred to 1,000 years (Allin et al. 2016), and some fraction of initially buried OC may be remineralized during this second transport stage (Thomson et al. 1987).

Type 3: submarine canyon that only partially indents the shelf, but sediment still reaches it from rivers. Approximately 30% of submarine canyons partly indent the shelf (Harris et al. 2014, Bernhardt & Schwanghart 2021), and at least in some cases, sediment is transferred effectively across the shelf to the canyon head, triggering turbidity currents (**Figure 3*c***). One example is the Bengal Fan fed by the Ganges and Brahmaputra Rivers, which alone carry ~8–10% of global sediment and ~2% of the terrestrial OC flux from continents to oceans (**Supplemental Table 1**). Clinoforms on the shelf reach the canyon head, which is highly active with turbidity currents (Rogers & Goodbred 2010). Similar amounts of (mainly fresh) terrestrial OC characterize sediment from both the river mouths and the deep-sea fan, suggesting highly (80–100%) efficient burial of OC, despite a distance of ~140 km from river mouths to the canyon head (Galy et al. 2007).

Supplemental Material >

The sediment flux to this system is extreme (Milliman & Farnsworth 2011), but sediment can be transferred effectively across the shelf in other locations, albeit for somewhat shorter distances. For example, ~60% of sediment from the Eel River is transferred across an ~12-km-wide shelf and is mostly trapped by a submarine canyon (Pratson et al. 2009). Cross-shelf sediment transport occurs via highly mobile mud layers that are often partly supported by waves or tides (Kineke et al. 1996, Kuehl et al. 1996, Wright & Friedrichs 2006) and thus may be favored by locations with greater tide or wave amplitudes. Similar fractions (60%) of river sediment traverse the 30–40-km-wide shelf offshore of the Waipaoa River in Aotearoa New Zealand to reach the Poverty Canyon head (Kuehl et al. 2016). There is also evidence for recent sediment deposition in the Mississippi Canyon head (Bianchi et al. 2006), although the distal parts of that large submarine fan are dormant (Piper et al. 1997, Schlünz et al. 1999). The burial flux of terrestrial OC in such systems is variable, for example, due to the fraction of sediment and sources of OC traversing the shelf, the residence time on the shelf, and the frequency of turbidity currents. But in some cases (e.g., the Bengal Fan), these systems may have terrestrial OC burial efficiencies of >50% to ~100% (Galy et al. 2007, Kuehl et al. 2016).

Type 4: submarine canyon that is restricted to the shelf edge but is still highly active. Approximately 70% of all submarine canyons are restricted to the shelf edge and continental slopes (Harris & Whiteway 2011, Harris et al. 2014) (**Figure 3*d***). For example, Whittard Canyon is located more than 300 km from the nearest coastline and does not indent the shelf (Amaro et al. 2016, Heijnen et al. 2022b). However, recent monitoring shows that it had 4–6 powerful (up to 5–8 m/s) turbidity currents in one year, some of which ran out for more than 50 km to water depths of >2 km (Heijnen et al. 2022b). It is thus as active as some canyons that connect directly to shorelines and littoral cells, such as type 2 Monterey Canyon (Paull et al. 2018). It was previously thought that present-day turbidity currents played little role in the transfer and burial of fresh (mainly marine) OC in Whittard Canyon (Amaro et al. 2016), with labile organic matter supplied to the canyon floor via vertical settling, but this was based mainly on moorings in deeper water (>4 km) (Amaro et al. 2016). Further work is needed to understand how sediment is supplied to such canyon heads, such as via sand waves on the shelf (Heijnen et al. 2022b), and how far turbidity currents extend down these types of canyons. But there are thousands of other submarine canyons restricted to the continental slope (Harris et al. 2014), and work in Whittard Canyon (Heijnen et al. 2022b) raises the question of how many of those canyons are currently active. Even if that activity is restricted to their upper reaches, they could play a role in global carbon cycling and delivery of OC to the deep ocean.

Type 5: submarine canyon that is at the shelf edge and assumed to be inactive. It is often assumed that submarine canyons restricted to the continental slope are currently inactive, because limited sediment can reach the canyon head, especially where the shelf is wide (**Figure 3*e***). For example, influential studies of the Amazon system show how terrestrial OC is reworked repeatedly on the shelf within highly mobile mud layers (Kuehl et al. 1996, Kineke et al. 1996, Nittrouer et al. 2021), which causes this OC to be repeatedly exposed to oxygen and remineralized, reducing burial efficiency to 20–30% (Aller 1998; Schlünz & Schneider 2000; Burdige 2005, 2007; Nittrouer et al. 2021). It has been inferred that negligible sediment reaches the Amazon Canyon head at the shelf edge because the continental shelf is ∼300 km wide (Nittrouer et al. 2021). Steep submerged delta foresets occur on the shelf ∼100 km from the canyon head, and monitoring shows that episodic flows of fluid mud move down these foresets (Sternberg et al. 1996, Nittrouer et al. 2021). Fluid muds can be extremely mobile on low gradients, moorings for flow monitoring are yet to be placed in the upper Amazon Canyon, and cores are not available to determine whether recent sedimentation occurs. Monitoring is warranted to confirm inactivity, especially given the activity seen in Whittard Canyon, also 300 km from shore. However, the outer Amazon shelf is dominated by sandy deposits and coral reefs, with little evidence of mud deposition from turbidity currents (Nittrouer et al. 2021, Vale et al. 2022), and reworked terrestrial OC that escapes from the shelf may have a high refractory component and thus play a limited role in drawdown of CO_2 from the atmosphere. Cores on levees from deeper (>2 km) parts of the Amazon Fan clearly indicate that overspill of large turbidity currents ceased during the last sea-level rise (Piper et al. 1999), and much greater burial of both marine and terrestrial OC occurred in the deep sea during lowstands in sea level (Schlünz et al. 1999).

Type 6: fjords where a river mouth feeds directly into deep water. Efficient burial of both terrestrial and marine OC occurs within fjords, which are often characterized by high TOC (average 2.6%), rapid sediment accumulation, and poorly oxygenated seabed conditions (Smith et al. 2015; Bianchi et al. 2018, 2020). Rapid transport of terrestrial OC from forests and soils, as well as episodic sediment supply from mountainous rivers, may also lead to a high percentage of fresh (biospheric) carbon (Smith et al. 2015; Cui et al. 2016; Bianchi et al. 2018, 2020; Smeaton & Austin 2022). Thus, even though their surface areas are ∼40 times smaller than those of deltas and continental shelves, fjords represent ∼17% of the global terrestrial OC burial and ∼11% of the TOC burial in marine sediments (Smith et al. 2015). Well-developed turbidity current systems occur in many (Pope et al. 2019; Hage et al. 2020, 2022) but not all (Smeaton & Austin 2022) fjords, and they can play a key role in OC cycling (**Figure 3*f***). Significant amounts of terrestrial OC are buried in the sandy parts of turbidites (Hage et al. 2020), suggesting that past global estimates of burial fluxes are underestimates, as they consider primarily muddy fjord sediments (Smith et al. 2015). Efficient burial of terrestrial OC can occur within fjord turbidites (Smith et al. 2015, Hage et al. 2020) (**Supplemental Material** and **Supplemental Table 1**) despite being remobilized in one or more stages by seabed flows (Heijnen et al. 2022a,b). For example, a detailed study of Bute Inlet suggested that 62% ± 10% of the OC supplied by the rivers is buried within surface marine sediment across this fjord (Hage et al. 2022).

Supplemental Material >

Type 7: mega-landslides and abyssal plains with infrequent but very large turbidity currents. Some submarine landslides are exceptionally large (Korup et al. 2007, Talling et al. 2014) (**Table 1**) and disintegrate to form turbidity currents that transport and deposit large amounts of OC in mega-turbidites in deep-water basin plains and trenches (**Figure 3*g***). Individual mega-landslides within submarine fan systems can be vast. For example, those on the Mississippi, Nile, and Amazon Fans contain 400–800 km^3 of sediment (e.g., Maslin et al. 2005), while landslide deposits are 10–20% of the total mass of the Congo Fan (Picot et al. 2015). Very large landslides also occur on open continental slopes away from canyon-fed fans, such as the Storegga landslide off Norway, which comprises >3,000 km^3 (Haflidason et al. 2005, Talling et al. 2014).

If a landslide fails to disintegrate, then OC is trapped within landslide deposits that may be tens of meters thick, so negligible OC is remineralized. However, when mega-landslides mix with seawater to form a turbidity current, very large sediment volumes may be spread in a thin turbidite layer across a very wide area in deep-water basin plains or trenches, remineralizing large amounts of OC (Thomson et al. 1987, Piper et al. 1999, Talling et al. 2007). These mega-turbidites in basin plains may originate from landslides on open continental slopes or via canyon-flushing turbidity currents. OC in the upper part of distal mega-turbidites is then remineralized over long periods of hundreds to thousands of years between events (Thomson et al. 1987). The fraction of OC that is lost from these mega-turbidites also depends on whether thick layers pond in basin lows, which then protects most underlying OC from surface oxidization (Thomson et al. 1987). Some submarine landslide events are triggered by earthquakes; the M_w 9.1 Tohoku earthquake in 2011 offshore Japan remobilized ~1 Mt of OC into a deep-sea trench (Kioka et al. 2019) (**Table 1**).

Importantly, in contrast to smaller canyon-filling flows, the frequency of mega-turbidites that reach abyssal basin plains appears to be independent of sea level (Allin et al. 2016) and quasi-random in time (Clare et al. 2014). This may reflect that the mega-flows that reach basin plains have exceptional and more temporally random triggers, such as earthquakes. Flows that flushed Nazaré Canyon and reached the Iberian Abyssal Plain have an average frequency of ~2,000 years and likely contained more than ~0.1–1 km^3 of sediment (Allin et al. 2016), implying a flux of more than ~0.1–1 Mt/year, which is comparable to sediment supply via longshore drift to the modern canyon head (Duarte et al. 2019). Thus, the turbidity current pump may remain active during lowstands of sea level through these exceptionally large but infrequent canyon-flushing turbidity currents, even in cases where canyon-filling flows are much reduced.

Do We Need to Revise the Global Amount and Efficiency of Organic Carbon Burial in Marine Sediments?

Current estimates of global burial of both marine and terrestrial OC in marine sediments are in the range of ~160–170 Mt C/year (Hedges & Keil 1995; Burdige 2005, 2007; Smith et al. 2015; Hilton & West 2020) (**Table 1**). This range was derived by assuming that 66% of the annual sediment mass flux from rivers (i.e., ~18,000 Mt/year; Milliman & Farnsworth 2011) is deposited in deltaic areas, while 33% is deposited on continental shelves and upper slopes (Hedges & Keil 1995, Burdige 2005). No OC was assumed to reach deep-sea submarine fans. Average TOC values of ~0.7% for deltas and 1.5% for shelves and slopes were used to compute OC burial fluxes, with a further ~22 Mt C/year assumed to be buried in marine sediment buried in other locations (e.g., beneath zones of high surface ocean productivity). It was then assumed that ~67% of the TOC in deltaic areas and ~16% in shelves and slopes are terrestrial OC. This led to an estimated burial flux of terrestrial OC in marine sediments of ~40–80 Mt/year (Burdige 2005, 2007, Hilton & West 2020) (**Table 1**). Rivers are estimated to supply ~200–300 Mt/year of terrestrial OC to the oceans (Galy et al. 2015, Hilton & West 2020, Li et al. 2022) (**Table 1**). This produces estimates of global burial efficiency for terrestrial OC in marine sediments of ~13–40% (**Table 1**; **Supplemental Material**).

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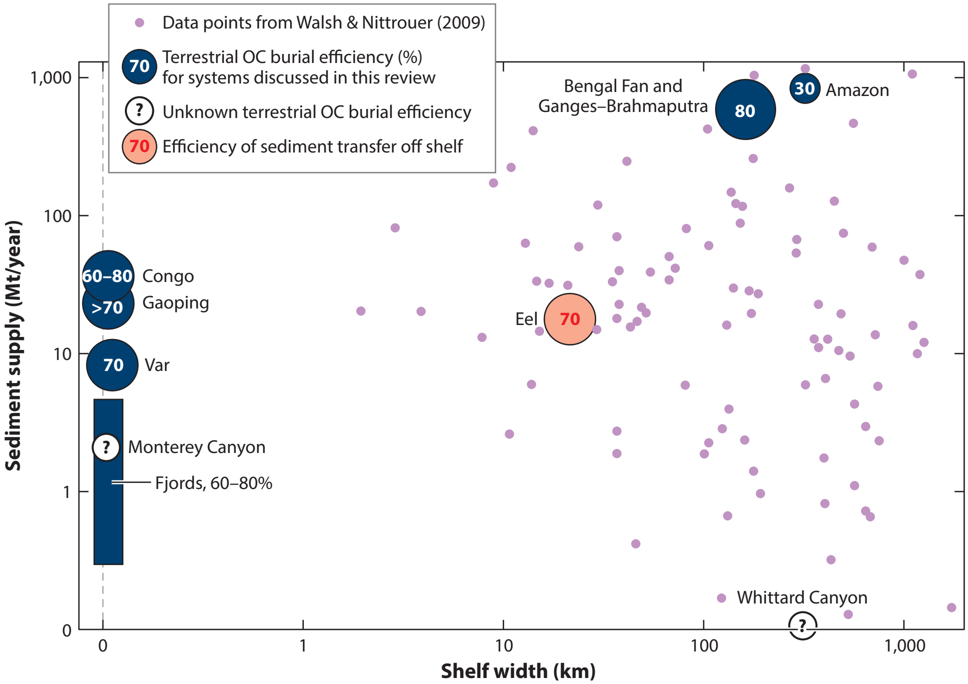

Figure 4

Relationship between the efficiency of sediment transfer and terrestrial OC burial, shelf width, and the magnitude of the annual sediment supply from rivers or via longshore drift (e.g., to Monterey Canyon). Data on annual sediment fluxes from rivers and shelf width are from Walsh & Nittrouer (2009). Annual sediment flux into the head of Whittard Canyon is poorly known but relatively low (Heijnen et al. 2022b). For the Eel River and the associated shelf, the fraction of riverine sediment that escapes the shelf on a decadal timescale is shown, rather than the estimated burial efficiency of OC. Abbreviation: OC, organic carbon.

Supplemental Material >

However, from our discussions above, terrestrial OC burial can be much more efficient than 40% in a wide range of settings (**Figure 4**; **Supplemental Material** and **Supplemental Tables 1 and 2**), such as type 1 systems that include the large Bengal Fan (Galy et al. 2007), Congo Fan (Baudin et al. 2020, Talling et al. 2022), Gaoping Canyon (Kao et al. 2014), and Mackenzie River (Hilton et al. 2015) systems as well as type 6 global fjords (Smith et al. 2015, Bianchi et al. 2020, Hage et al. 2022). Some forms of terrestrial carbon thus appear able to survive repeated mobilization and long-distance transfer (Blair & Aller 2012). It is therefore timely to reassess values for global burial of OC in marine sediments.

Three methods can be used to calculate global fluxes and burial efficiency of terrestrial OC. The first method uses the global OC flux from rivers and attributes it in different proportions to different settings, such as deltas, shelves, submarine fans, or fjords (Berner 1982, 1989; Burdige 2005, 2007; Blair & Aller 2012). This method neglects annual sediment supply to canyon heads via longshore drift, which may be significant, include a component of coastal erosion, and not necessarily reflect the closest river (e.g., Gibbs et al. 2020). It is therefore not preferred here. The amount of sediment reaching the ocean from rivers globally has also declined due to human activities (e.g., dams) and may now be ~50% (Syvitski et al. 2022) of the value of ~18,000 Mt/year (Milliman & Farnsworth 2011) that was used to infer that 40–80 Mt/year of terrestrial OC is buried in marine sediments. This raises a question of whether terrestrial OC burial in the oceans has also declined by up to 50%, with a greater amount of OC buried in reservoirs and terrestrial settings. However, dams may preferentially trap sandy bedload with lower amounts of fresh OC (Bianchi et al. 2018, Syvitski et al. 2022), and rates of sediment deposition in coastal areas offshore North America do not seem to have declined since 1950 (Dethier et al. 2022).

A second method uses the abundance of terrestrial OC and sediment accumulation rates measured in seabed sediment cores together with representative areas to calculate burial fluxes (Smith et al. 2015; Cartapanis et al. 2016, 2018; Rabouille et al. 2019; Baudin et al. 2020; Li et al. 2022). Although this method is currently not feasible due to spatially limited OC measurements in cores from turbidite systems, it holds promise for future estimates of terrestrial OC burial in submarine fans by extending published core data for submarine fan accumulation rates (e.g., Covault & Graham 2010) to include TOC and terrestrial OC fractions. It should also be noted that cores from submarine fans may be significantly underrepresented in global core databases previously used for TOC burial estimates in marine sediments (Cartapanis et al. 2016, 2018; Li et al. 2022). Furthermore, sandy seabed areas are often impractical to core via traditional piston or gravity corers, potentially leading to other biases.

A third method is to estimate burial efficiencies in a small number of well-studied locations or system types with larger OC burial fluxes—namely, (*a*) the Ganges–Brahmaputra system and Bengal Fan, (*b*) the Congo River and Fan, and (*c*) the Amazon and Fly Rivers and their offshore areas, as well as (*d*) Oceania systems (derived from Taiwan; see the **Supplemental Material**), (*e*) fjords, and (*f*) all other systems not included in the first five categories (**Supplemental Material** and **Supplemental Table 1**). The percentage of global OC supplied by rivers to each of these categories is calculated for both TOC and OC_{bio}. A range of burial efficiencies of terrestrial OC in marine sediments is then defined for each system (**Supplemental Table 1**). For example, we assume a burial efficiency of 80–90% for the Bengal Fan (Galy et al. 2007), 60–90% for the Congo Fan (Azpiroz-Zabala et al. 2017, Baudin et al. 2020, Talling et al. 2022), 60–80% for fjords (Smith et al. 2015, Bianchi et al. 2020), 60–90% for systems in Oceania fed by small mountainous rivers (Kao et al. 2014, Bao et al. 2015), and 30% for the Amazon and Fly River shelves (figure 9 in Blair & Aller 2012). Burial efficiencies of 20% and 30% are then modeled for the final category (all other systems) (**Supplemental Material** and **Supplemental Table 1**). The fraction of global TOC and OC_{bio} supply buried within seabed sediment is then calculated for each of these categories, which are then summed to derive an overall global burial efficiency for TOC and OC_{bio} (for details and justification of the values chosen in **Supplemental Table 1**, see the **Supplemental Material**).

Supplemental Material >

This method derives a global burial efficiency of 31–45% for terrestrial OC in marine sediments and 28–51% for OC_{bio} (for details, see the **Supplemental Material** and **Supplemental Table 1**). This range is significantly higher than the burial efficiencies of 10–30% proposed by Hedges et al. (1997), Schlünz & Schneider (2000), and Burdige (2005, 2007) and somewhat greater than the 20–44% estimate of Blair & Aller (2012) (**Table 1**). Using the revised terrestrial OC burial efficiency of 31–45% and a flux of 200 Mt/year of terrestrial OC from rivers (Galy et al. 2015), we derive a burial flux of terrestrial OC in marine sediments of 62–90 Mt/year, which is higher than the previous values of 40–80 Mt/year (Hilton & West 2020) (**Table 1**).

How Do Glacial Sea-Level Cycles Affect Global Organic Carbon Burial Efficiency in Marine Sediments?

Far more rivers connect directly to the heads of submarine canyons during glacial periods due to the lower global sea level (Harris et al. 2014, Bernhardt & Schwanghart 2021) (**Figure 3*b***), and this profoundly affects the transfer and burial of OC in the deep sea. Numerous submarine fans would therefore likely have burial efficiencies for terrestrial OC of >60% to almost 100%, as occurs in modern type 1 systems, where river mouths connect to canyon heads (**Figures 3*a*** and **4**), such as the Congo Fan and Bengal Fan, or small mountainous rivers in Oceania, exemplified by the

Supplemental Material >

Gaoping Canyon system (**Supplemental Material** and **Supplemental Table 1**). The global burial efficiency of terrestrial OC in marine sediments would thus potentially reach 60–80% during glacial periods, rising significantly from the values of 31–45% derived in the previous section and past estimates of 10–44% (**Table 1**). If it is also assumed that the flux of OC (200 Mt/year; **Table 1**) from land did not change, which is supported by an overall erosional control on OC export in river sediments (Galy et al. 2015, Hilton 2017), and ∼10–15 Mt/year of terrestrial OC was buried within glacial trough-mouth fans, then burial of terrestrial OC in marine sediment during glacial periods would increase from 62–90 Mt/year to 130–175 Mt/year (**Table 1**; **Supplemental Material**). Assuming that burial of marine OC from surface oceans (90–130 Mt/year) remained unchanged, the TOC burial flux in marine sediments would rise to 220–305 Mt/year. However, we also note that sediment and OC export from rivers to the ocean may vary systematically and significantly between glacial and interglacial periods (e.g., Mariotti et al. 2021).

Our analysis suggests that the total amount of OC buried in marine sediments may have nearly doubled during glacial periods, reflecting an increase in terrestrial OC burial efficiency from 31–45% to 60–80% (**Table 1**). A similar doubling of TOC burial within deep-sea (>1 km) cores was noted by Cartapanis et al. (2016) (**Figure 5*a***). However, they only considered sites at water depths of >1 km and omitted submarine fans built by turbidity currents, and the OC burial fluxes they calculated were therefore ∼10% of those calculated here (**Figure 5*a***; **Table 1**). Cartapanis et al. (2016) attributed the increased OC burial in marine sediments to enhanced nutrient supply, better preservation of organic matter due to reduced oxygen exposure, and more efficient transfer of terrestrial organic matter to the deep sea by turbidity currents.

This raises the question of how highly variable burial flux of OC in marine sediment affects global carbon cycling and atmospheric pCO_2 levels, and thus climate (Cartapanis et al. 2016, 2018, Li et al. 2022). Burial of OC in marine sediment affects atmospheric CO_2 levels only over long timescales (>1,000 years) (Galy et al. 2007, Blair & Aller 2012, Hilton & West 2020). Over shorter time periods (days or months to millennia), atmospheric pCO_2 is determined by exchange of CO_2 between the atmosphere, ocean-water reservoirs, and terrestrial biomass (Sundquist 1993). Interaction between these shorter-term (active) carbon reservoirs and longer-term (geological) reservoirs such as marine sediments can be complex, not least because many factors other than the turbidity current pump likely varied between glacial and interglacial periods (Sigman & Boyle 2000, Cartapanis et al. 2016). For example, increased surface-ocean productivity is commonly inferred to have reduced atmospheric pCO_2 levels during glacial periods, thus amplifying reductions in atmospheric pCO_2 (Sigman & Boyle 2000). More efficient burial of OC by the turbidity current pump would also be a positive feedback (Galy et al. 2007; Cartapanis et al. 2016, 2018), further reducing pCO_2 levels during glacial periods but over much longer timescales (>1,000 years). However, the magnitude of change in OC burial flux via turbidity currents between glacial and interglacial periods (∼30–95 Mt/year; **Table 1**) may rival or exceed changes in global OC burial previously proposed to drive other longer-term climate fluctuations (**Figure 5**). For example, Li et al. (2023) inferred that moderate changes in global OC burial flux (e.g., ∼90 Mt/year) were an important positive feedback for global warming during the Neogene (∼23–3 Ma) (**Figure 5*b***).

The Role of Turbidity Currents in Terrestrial Organic Carbon Cycling by Ice Sheets

Large fluctuations in OC storage and release can also occur due to the growth and decay of ice sheets (Zeng 2003, 2007; Wadham et al. 2019; Cui et al. 2022), and turbidity currents may play some role in such OC storage and release. For example, terrestrial OC may be buried beneath ice sheets during glacial periods but efficiently remineralized as ice sheets melt (Zeng 2003, 2007). Fjords at the margins of ice sheets may then bury the OC that is released from within or below

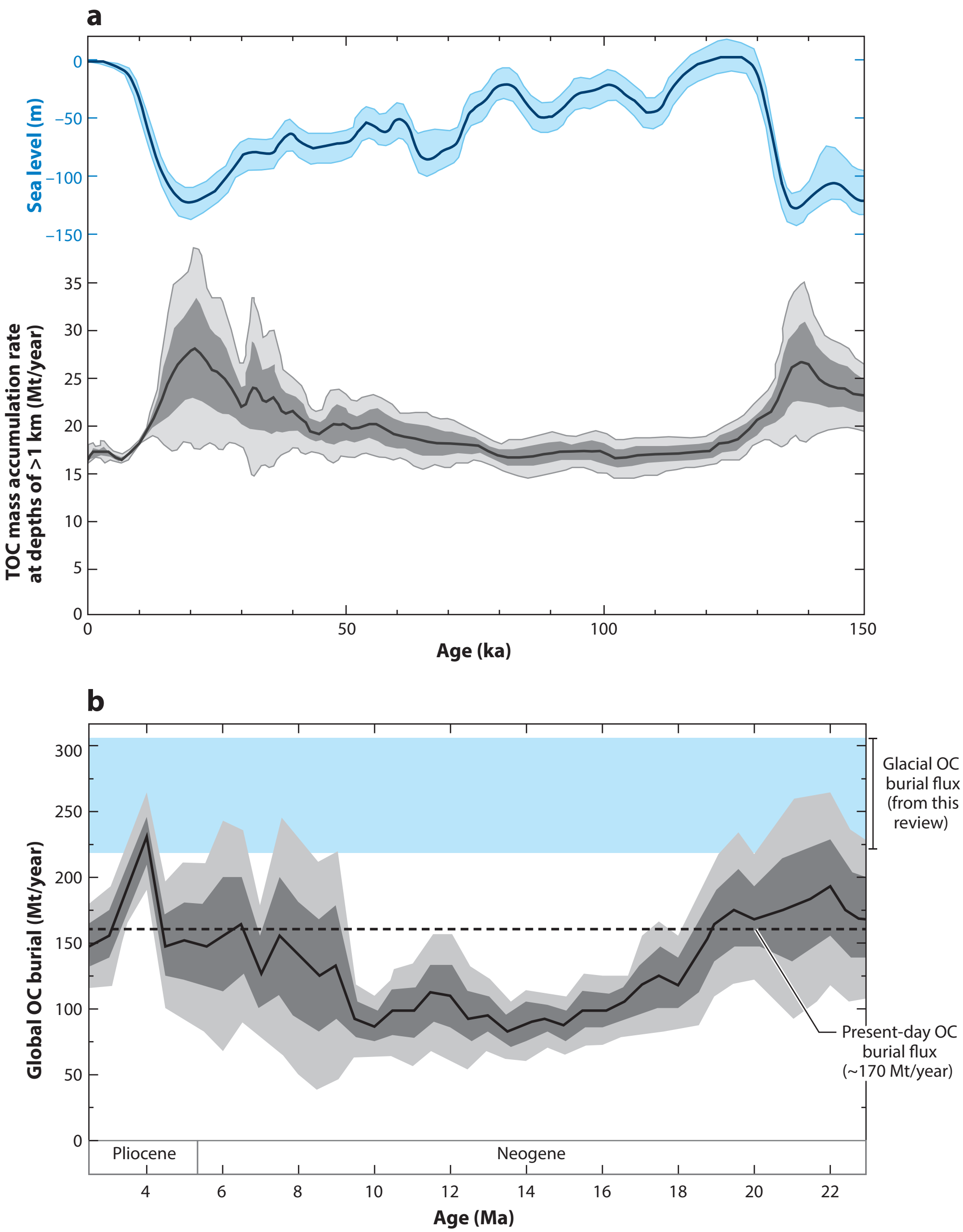

Figure 5

Changes in TOC burial flux within marine sediments through time. Burial fluxes are calculated by using seabed core databases and analyses of TOC, mass accumulation rates, and representative areas (biogeographic provinces). (*a*) Changes in TOC burial flux in the deep sea (>1-km water depth) during glacial and interglacial periods. Submarine fans were not included within Cartapanis et al.'s (2016) seabed core database, suggesting that they may have underestimated OC burial fluxes. Here, we estimate a global OC burial flux during glacials of 220–305 Mt/year, much of which will occur via turbidity currents on submarine fans at water depths of >1 km. (*b*) Longer-term changes in global OC burial rates over the last ~23 Ma from Li et al. (2023), who inferred that changes may have affected global climate. Abbreviations: OC, organic carbon; TOC, total organic carbon. Panel *a* adapted from Cartapanis et al. (2016) (CC BY 4.0); panel *b* adapted with permission from Li et al. (2023).

glaciers as sea level rises during deglaciation (Smith et al. 2015, Cui et al. 2022). Turbidity current systems will play a role in how OC is buried within many such fjords (Smith et al. 2015, Hage et al. 2020).

In addition, when ice streams reach the shelf edge, they can form extremely large-volume sediment accumulations (called trough-mouth fans), whose scale rivals that of the largest river-fed submarine fans (Nygård et al. 2007). For example, the sediment mass flux to the North Sea Trough-Mouth Fan at the peak of the last glacial was ~1,100 Mt/year, which occurred for only ~1,000 years (Nygård et al. 2007). This sediment flux is similar to those of the modern Amazon and Ganges–Brahmaputra River systems (Milliman & Farnsworth 2011). Terrestrial OC burial is highly efficient within these episodically active trough-mouth fans, which are built by thick submarine debris flow deposits and turbidites (Nygård et al. 2007, Bellwald et al. 2020). Therefore, trough-mouth fans need to be included in estimates of global terrestrial OC burial in marine sediments during glacial periods (**Figure 3*i***), although it is likely that they contain a high fraction of fossil OC and relatively low TOC (King et al. 1998). For example, if trough-mouth fans globally supplied 2,000–3,000 Mt/year of sediment with TOC values of ~0.5% (King et al. 1998), this would be an additional burial flux of 10–15 Mt/year of terrestrial OC in marine sediments, raising the global burial flux to 130–175 Mt/year (**Table 1**).

CONCLUSIONS

Turbidity currents are one of the most important sediment transport processes (pumps) on Earth (Talling et al. 2015), yet they were previously not included in analyses of global OC cycles (Berner 1982, 1989; Burdige 2005, 2007; Blair & Aller 2012). It was once assumed that terrestrial OC was primarily incinerated on continental shelves, such that global burial efficiency was low (~10–44%; **Table 1**), and that the vast majority of turbidity current systems were inactive in the modern sea-level highstand (Berner 1982, 1989; Posamentier & Kolla 2003). However, it is now emerging that deep-sea burial of terrestrial OC by turbidity currents can be highly efficient (~60–100%) in a relatively wide range of settings (Galy et al. 2007, Kao et al. 2014, Smith et al. 2015, Baudin et al. 2020) (**Supplemental Table 1**). Direct monitoring and dated cores are also showing that turbidity currents are presently much more active than once thought (e.g., Clare et al. 2016, Normandeau et al. 2020, Heijnen et al. 2022b, Talling et al. 2022), and they would be even more active in glacial sea-level lowstands (Schlünz et al. 1999, Harris et al. 2014, Cartapanis et al. 2016).

Supplemental Material >

The role of turbidity currents in global carbon cycling is therefore in need of reassessment, leading to revised global estimates for the mass flux (~62–90 Mt/year) and efficiency (31–45%) of terrestrial OC burial in marine sediments (**Table 1**; **Supplemental Material**). Burial of terrestrial OC during glacial periods of sea-level lowstand was far more efficient than it is at present, as most submarine canyons connected to river mouths (Harris & Whiteway 2011, Bernhardt & Schwanghart 2021). We estimate that terrestrial OC burial doubled during glacial periods, and this is consistent with previous analysis of deep-sea (>1 km) cores (**Figure 5*a***). Assuming a global average burial efficiency of 60–80% by turbidity currents, the TOC burial flux in marine sediments could rise to 220–305 Mt/year (**Table 1**). Similar changes in seabed burial flux of OC from surface-ocean carbon pumps are thought to be an important positive-feedback mechanism for global warming (Li et al. 2023) (**Figure 5*b***). The fluctuating strength of the turbidity current pump may therefore also affect atmospheric pCO_2 levels and climate over longer geological timescales (≫1,000 years) (Galy et al. 2007, Kao et al. 2014, Cartapanis et al. 2016).

FUTURE RESEARCH DIRECTIONS

This review is a rallying call for additional flow monitoring, allied to time-lapse bathymetric mapping and sediment sampling, to understand the frequency and nature of turbidity currents in a much wider range of settings. This direct monitoring work can then underpin better-constrained estimates of mass transfer and burial fluxes of OC within marine sediments. Ideally, new methods are needed to measure sediment concentrations and mass fluxes directly in turbidity currents (e.g., Simmons et al. 2020), which are currently estimated via time-lapse mapping (Hage et al. 2022, Heijnen et al. 2022a, Talling et al. 2022) or dating of widely spaced sediment cores (Covault & Graham 2010).

There is also a need to understand where and how sediment and OC are transferred efficiently across wide (≫10 km) continental shelves (**Figures 2*d*** and **4**), as this may produce a far greater number of active submarine canyons (Harris & Whiteway 2011, Bernhardt & Schwanghart 2021). Whittard Canyon is more than 300 km from the nearest coast, yet it is currently active (Heijnen et al. 2022b). Future work should aim to determine the ultimate fate of extremely mobile (fluid) mud layers on the continental shelf (Kineke et al. 1996, Wright & Friedrichs 2006, Kuehl et al. 2016, Nittrouer et al. 2021) and whether they occasionally escape the shelf, as these fluid muds occur on some of the largest systems that have a disproportionate effect on global fluxes. For example, it is often assumed that the Amazon (Nittrouer et al. 2021) and Mississippi Canyons are inactive, but moored sensors have not yet been placed in these canyons, and dated cores from the upper Mississippi Canyon suggest recent flows (Bianchi et al. 2002).

Finally, improved estimates of global OC burial fluxes are based on seabed core databases, both for the Quaternary (Cartapanis et al. 2016) and older geological periods (Li et al. 2023); however, these core databases are strongly biased, as they have few or no cores from submarine fans (Cartapanis et al. 2016, Li et al. 2023), where sediment and OC accumulation rates are unusually high (Baudin et al. 2020) (**Figure 2**). Future studies thus need to include representative cores from submarine fans. Traditional coring methods tend not to recover sandy sediments, and there should also be efforts to account for OC buried within sandy sediment, including with studies of modern carbon stock on continental shelves (Atwood et al. 2020).

This article has focused on how more efficient organic carbon burial by turbidity currents may affect long-term climate change, but organic carbon is also the basis for most marine food webs. Transfer of organic carbon by turbidity current may therefore also have significant implications for seabed life (see the sidebar titled Wider Implications of the Turbidity Current Pump).

WIDER IMPLICATIONS OF THE TURBIDITY CURRENT PUMP

A more active turbidity current carbon pump has significant implications for seabed life. These flows supply OC that underpins food webs, although seafloor biomass is more dependent on labile marine carbon than the refractory terrestrial carbon that dominates some flows (Gibbs et al. 2020, Leduc et al. 2020). Powerful turbidity currents both scour the seabed, sometimes to depths of tens of meters, and deposit thick sediment layers that smother ecosystems (Mountjoy et al. 2018). Rapid accumulation of organic-rich sediment has sometimes favored chemotrophic ecosystems resembling those around black smokers (Karine et al. 2017), while turbidity currents provide a template of sediment or bedrock types for different ecosystems.

There is an increasing focus on how carbon stocks on continental shelves are remobilized by human activities such as trawling (Atwood et al. 2020). Where trawling occurs close to canyons, turbidity currents play a key role in exporting and remineralizing carbon (Puig et al. 2012, Payo-Payo et al. 2017, Paradis et al. 2022). Turbidity currents may also transfer microplastics in the deep sea, potentially explaining why ∼99% of plastic entering the ocean is currently unaccounted for (Kane & Clare 2019). There is also a question of whether onshore water reservoirs, which may now trap ∼50% of global river sediment (Syvitski et al. 2022), affect offshore turbidity currents and their carbon cycling.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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LITERATURE CITED

Aller RC. 1998. Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors. *Mar. Chem.* 61:143–55

Aller RC, Blair NE. 2006. Carbon remineralization in the Amazon-Guianas mobile mudbelt: a sedimentary incinerator. *Cont. Shelf Res.* 26:2241–59

Aller RC, Madrid V, Chistoserdov A, Aller JY, Heilbrun C. 2010. Unsteady diagenetic processes and sulfur biogeochemistry in tropical deltaic muds: implications for oceanic isotope cycles and the sedimentary record. *Geochim. Cosmochim. Acta* 74:4671–92

Allin JR, Hunt JE, Talling PJ, Clare ME, Pope E, Masson DG. 2016. Different frequencies and triggers of canyon filling and flushing events in Nazaré Canyon, offshore Portugal. *Mar. Geol.* 371:89–105

Allison MA, Bianchi TS, McKee BA, Sampere TP. 2007. Carbon burial on river-dominated continental shelves: impact of historical changes in sediment loading adjacent to the Mississippi River. *Geophys. Res. Lett.* 3:L01606

Amaro T, Huvenne VAI, Allcock AL, Aslam T, Davies JS, et al. 2016. The Whittard Canyon – a case study of submarine canyon processes. *Prog. Oceanogr.* 146:38–57

Aplin AC, Fleet AJ, Macquaker JHS. 1999. Muds and mudstones: physical and fluid-flow properties. In *Muds and Mudstones: Physical and Fluid-Flow Properties*, ed. AC Aplin, AJ Fleet, JHS Macquaker, pp. 1–8. Geol. Soc. Spec. Publ. 158. London: Geol. Soc.

Arndt S, Jørgensen BB, LaRowe DE, Middelburg JJ, Pancost RD, Regnier P. 2013. Quantifying the degradation of organic matter in marine sediments: a review and synthesis. *Earth-Sci. Rev.* 123:53–86

Atwood TB, Witt A, Mayorga J, Hammill E, Sala E. 2020. Global patterns in marine sediment carbon stocks. *Front. Mar. Sci.* 7:165

Azpiroz-Zabala M, Cartigny MJB, Talling PJ, Parsons DR, Sumner EJ, et al. 2017. Newly recognised turbidity current structure can explain prolonged flushing of submarine canyons. *Sci. Adv.* 3:e1700200

Bailey LP, Clare MA, Rosenberger K, Cartigny MJB, Talling PJ, et al. 2021. Preconditioning by sediment accumulation can produce powerful turbidity currents without major external triggers. *Earth Planet. Sci. Lett.* 562:116845

Bao H, Lee T-Y, Huang J-C, Feng X, Dai M, Kao S-J. 2015. Importance of Oceanian small mountainous rivers (SMRs) in global land-to-ocean output of lignin and modern biospheric carbon. *Sci. Rep.* 5:16217

Bao R, van der Voort TS, Zhao M, Guo X, Montluçon DB, et al. 2018. Influence of hydrodynamic processes on the fate of sedimentary organic matter on continental margins. *Glob. Biogeochem. Cycles* 32:1420–32

Baudin F, Rabouille C, Dennielou B. 2020. Routing of terrestrial organic matter from the Congo River to the ultimate sink in the abyss: a mass balance approach. *Geol. Belg.* 23:41–52

Bauer JE, Cai WJ, Raymond P, Bianchi TS, Hopkinson CS, Regnier P. 2013. The coastal ocean as a key dynamic interface in the global carbon cycle. *Nature* 504:61–70

Bellwald B, Planke S, Becker LWM, Myklebust R. 2020. Meltwater sediment transport as the dominating process in mid-latitude trough mouth fan formation. *Nat. Commun.* 11:4645

Berner RA. 1982. Burial of organic carbon and pyrite sulfur in the modern ocean: its geochemical and environmental significance. *Am. J. Sci.* 282:451–73

Berner RA. 1989. Biogeochemical cycles of carbon and sulfur and their effect on atmospheric oxygen over Phanerozoic time. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 73:97–122

Bernhardt A, Schwanghart W. 2021. Where and why do submarine canyons remain connected to the shore during sea-level rise? Insights from global topographic analysis and Bayesian regression. *Geophys. Res. Lett.* 48:e2020GL092234

Bianchi TS. 2011. The role of terrestrially derived organic carbon in the coastal ocean: a changing paradigm and the priming effect. *PNAS* 49:19473–81

Bianchi TS, Arndt S, Austin WEN, Benn DI, Bertrand S, et al. 2020. Fjords as aquatic critical zones (ACZs). *Earth-Sci. Rev.* 203:10345

Bianchi TS, Blair N, Burdige D, Eglinton TI, Galy V. 2018. Centers of organic carbon burial at the land-ocean interface. *Org. Geochem.* 115:138–55

Bianchi TS, Mitra S, McKee B. 2002. Sources of terrestrially-derived carbon in the Lower Mississippi River and Louisiana shelf: implications for differential sedimentation and transport at the coastal margin. *Mar. Chem.* 77:211–23

Bianchi TS, Sampere T, Allison M, Canuel EA, McKee BA, et al. 2006. Rapid export of organic matter to the Mississippi Canyon. *Eos Trans. AGU* 87:565–73

Bianchi TS, Schreiner KM, Smith RW, Burdige DJ, Woodward S, Conley DJ. 2016. Redox effects on organic matter storage in coastal sediments during the Holocene: a biomarker/proxy. *Annu. Rev. Earth Planet. Sci.* 44:295–319

Blair NL, Aller RC. 2012. The fate of terrestrial organic carbon in the marine environment. *Annu. Rev. Mar. Sci.* 4:401–23

Blattmann TM, Liu Z, Zhang Y, Zhao Y, Eglinton TI. 2019. Mineralogical control on the fate of continentally derived organic matter in the ocean. *Science* 366:742–45

Bonneau L, Jorry SJ, Toucanne S, Silva Jacinto R, Emmanuel L. 2014. Millennial-scale response of a Western Mediterranean River to Late Quaternary climate changes: a view from the deep sea. *J. Geol.* 122:687–703

Burdige DJ. 2005. Burial of terrestrial organic matter in marine sediments: a re-assessment. *Glob. Biogeochem. Cycles* 19:GB4011

Burdige DJ. 2007. Preservation of organic matter in marine sediments: controls, mechanisms, and an imbalance in sediment organic carbon budgets? *Chem. Rev.* 107:467–85

Cartapanis O, Bianchi D, Jaccard SL, Galbraith ED. 2016. Global pulses of organic carbon burial in deep-sea sediments during glacial maxima. *Nat. Commun.* 7:10796

Cartapanis O, Galbraith ED, Bianchi D, Jaccard SL. 2018. Carbon burial in deep-sea sediment and implications for oceanic inventories of carbon and alkalinity over the last glacial cycle. *Clim. Past* 14:1819–50

Clare MA, Hughes Clarke JE, Talling PJ, Cartigny MJ, Pratomo DG. 2016. Preconditioning and triggering of offshore slope failures and turbidity currents revealed by most detailed monitoring yet at a fjord-head delta. *Earth Planet. Sci. Lett.* 450:208–20

Clare MA, Talling PJ, Challenor P, Malgesini M, Hunt JE. 2014. Distal turbidite records reveal a common distribution for large (>0.1 km^3) submarine landslide recurrence. *Geology* 42:263–66

Covault JA. 2011. Submarine fans and canyon-channel systems: a review of processes, products, and models. *Nat. Educ. Knowl.* 3(10):4

Covault JA, Graham SA. 2010. Submarine fans at all sea-level stands: tectono-morphologic and climatic controls on terrigenous sediment delivery to the deep sea. *Geology* 38:939–42

Cui X, Bianchi TS, Savage C, Smith RW. 2016. Organic carbon burial in fjords: terrestrial versus marine inputs. *Earth Planet. Sci. Lett.* 451:41–50

Cui X, Mucci A, Bianchi TS, He D, Vaughn D, et al. 2022. Global fjords as transitory reservoirs of labile organic carbon modulated by organo-mineral interactions. *Sci. Adv.* 8:eadd06

Dennielou B, Droz L, Babonneau N, Jacq C, Bonnel C, et al. 2017. Morphology, structure, composition and build-up processes of the active channel-mouth lobe complex of the Congo deep-sea fan with inputs from remotely operated underwater vehicle (ROV) multibeam and video surveys. *Deep-Sea Res. II* 142:25–49
Dethier EN, Renshaw CE, Magilligan FJ. 2022. Rapid changes to global river suspended sediment flux by humans. *Science* 376:1447–52
Duarte J, Taborda R, Ribeiro M. 2019. Evidences of headland sediment bypassing at Nazaré Norte Beach, Portugal. *Coast. Sediments* 2019:2685–94
Dunne JP, Darmiento JL, Gnanadesikan A. 2007. Synthesis of global particle export from the surface ocean and cycling through ocean interior and on the seafloor. *Glob. Biogeochem. Cycles* 21:GB4006
Ebelmen J. 1845. Sur les produits de la décomposition des especes minérales de la famille des silicates. *Ann. Mines* 7:3–66
Eglinton TI, Galy VV, Hemingway JD, Feng X, Bao H, et al. 2021. Climate control on terrestrial biospheric carbon turnover. *PNAS* 118:e2011585118
Gaillardet J, Dupré B, Louvat P, Allègre CJ. 1999. Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers. *Chem. Geol.* 159:3–30
Galvez ME, Gaillardet J. 2012. Historical constraints on the origins of the carbon cycle concept. *C. R. Geosci.* 344:549–67
Galy VV, France-Lanord C, Beyssac O, Faure P, Kudrass H, Palhol F. 2007. Efficient organic carbon burial in the Bengal Fan sustained by the Himalayan erosional system. *Nature* 450:407–10
Galy VV, Peucker-Ehrenbrink B, Eglinton T. 2015. Global carbon export from the terrestrial biosphere controlled by erosion. *Nature* 52:204–207
Gavey R, Carter L, Liu JT, Talling PJ, Hsu R, et al. 2017. Frequent sediment density flows during 2006 to 2015 triggered by competing seismic and weather cycles: observations from subsea cable breaks off southern Taiwan. *Mar. Geol.* 384:147–58
Gibbs M, Leduc D, Nodder SD, Kingston A, Swales A, et al. 2020. Novel application of a compound-specific stable isotope (CSSI) tracking technique demonstrates connectivity between terrestrial and deep-sea ecosystems via submarine canyons. *Front. Mar. Sci.* 7:608
Gruber N, Bakker DCE, DeVries T, Gregor L, Hauck J, et al. 2023. Trends and variability in the ocean carbon sink. *Nat. Rev. Earth Environ.* 4:119–34
Haflidason H, Lien R, Sjerup HP, Forsberg CF, Bryn P. 2005. The dating and morphometry of the Storegga Slide. *Mar. Pet. Geol.* 22:123–36
Hage S, Cartigny MJB, Sumner EJ, Clare MA, Hughes Clarke JE, et al. 2019. Direct monitoring reveals initiation of turbidity currents from extremely dilute river plumes. *Geophys. Res. Lett.* 46:11310–20
Hage S, Galy VV, Cartigny MJB, Acikalin S, Clare MA, et al. 2020. Efficient preservation of young terrestrial organic carbon in sandy turbidity current deposits. *Geology* 48:882–87
Hage S, Galy VV, Cartigny MJB, Heerema C, Heijnen MS, et al. 2022. Turbidity currents can dictate organic carbon fluxes across river-fed fjords: an example from Bute Inlet (BC, Canada). *J. Geophys. Res.* 127:e2022JG006824
Harris PT, Macmillan-Lawler M, Rupp J, Baker EK. 2014. Geomorphology of the oceans. *Mar. Geol.* 352:4–24
Harris PT, Whiteway T. 2011. Global distribution of large submarine canyons: geomorphic differences between active and passive continental margins. *Mar. Geol.* 285:69–86
Hartnett HE, Keil RG, Hedges JI, Devol AH. 1998. Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. *Nature* 391:572–75
Hasholt B, Nielsen TF, Mankoff KD, Gkinis V, Overeem I. 2022. Sediment concentrations and transport in icebergs, Scoresby Sound, East Greenland. *Hydrol. Process.* 36:e14668
Haughton PDW, Barker SP, McCaffrey WD. 2003. 'Linked' debrites in sand-rich turbidite systems – origin and significance. *Sedimentology* 50:459–482
Hayes CT, Costa KM, Anderson RF, Calvo E, Chase Z, et al. 2021. Global ocean sediment composition and burial flux in the deep sea. *Glob. Biogeochem. Cycles* 35:e2020GB006769
Hedges JI, Keil RG. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. *Mar. Chem.* 49:81–115
Hedges JI, Keil RG, Benner R. 1997. What happens to terrestrial organic matter in the ocean? *Org. Geochem.* 27:195–212

Heijnen MS, Clare MA, Cartigny MJB, Talling PJ, Hage S, et al. 2020. Rapidly-migrating and internally-generated knickpoints can control submarine channel evolution. *Nat. Commun.* 11:3129
Heijnen MS, Clare MA, Cartigny MJB, Talling PJ, Hage S, et al. 2022a. Fill, flush or shuffle: How is sediment carried through submarine channels to build lobes? *Earth Planet. Sci. Lett.* 584:117481
Heijnen MS, Mienis F, Gates AR, Bett BJ, Hall AR, et al. 2022b. Challenging the highstand-dormant paradigm for land-detached submarine canyons. *Nat. Commun.* 13:3448
Hemingway JD, Rothman DH, Grant KE, Rosengard SZ, Eglinton TI, et al. 2019. Mineral protection regulates long-term global preservation of natural organic carbon. *Nature* 570:228–31
Hill PR, Lintern DG. 2022. Turbidity currents on the open slope of the Fraser Delta. *Mar. Geol.* 445:106738
Hilton RG. 2017. Climate regulates the erosional carbon export from the terrestrial biosphere. *Geomorphology* 277:118–32
Hilton RG, Galy A, Hovius N, Chen M-C, Horng M-J, Chen H. 2008. Tropical-cyclone-driven erosion of the terrestrial biosphere from mountains. *Nat. Geosci.* 1:759–62
Hilton RG, Galy V, Gaillardet J, Dellinger M, Bryant C, et al. 2015. Erosion of organic carbon in the Arctic as a geological carbon dioxide sink. *Nature* 524:84–87
Hilton RG, West AJ. 2020. Mountains, erosion and the carbon cycle. *Nat. Rev. Earth Environ.* 1:284–99
Hodgson DM, Peakall J, Maier KL. 2022. Submarine channel mouth settings: processes, geomorphology, and deposits. *Front. Earth Sci.* 10:790320
Houghton RA. 2007. Balancing the global carbon budget. *Annu. Rev. Earth Planet. Sci.* 35:313–47
Hughes Clarke JE. 2016. First wide-angle view of channelized turbidity currents links migrating cyclic steps to flow characteristics. *Nat. Commun.* 7:11896
Hussein A, Haughton PDW, Shannon PM, Morris EA, Pierce CS, Omma JE. 2021. Mud-forced turbulence dampening facilitates rapid burial and enhanced preservation of terrestrial organic matter in deep-sea environments. *Mar. Pet. Geol.* 130:105101
Jickells TD, An ZS, Andersen KK, Baker AR, Bergametti G, et al. 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* 308:67–71
Kane IA, Clare MA. 2019. Dispersion, accumulation, and the ultimate fate of microplastics in deep-marine environments: a review and future directions. *Front. Earth Sci.* 7:80
Kao S-J, Dai M, Selvaraj K, Zhai W, Cai P, et al. 2010. Cyclone-driven deep sea injection of freshwater and heat by hyperpycnal flow in the subtropics. *Geophys. Res. Lett.* 37:L21702
Kao S-J, Hilton RG, Selvaraj K, Dai M, Zehetner H, et al. 2014. Preservation of terrestrial organic carbon in marine sediments offshore Taiwan: mountain building and atmospheric carbon dioxide sequestration. *Earth Surf. Dyn.* 2:127–39
Karine O, Decker C, Pastor L, Caprais J-C, Khripounoff A, et al. 2017. Cold-seep-like macrofaunal communities in organic- and sulfide-rich sediments of the Congo deep-sea fan. *Deep-Sea Res. II* 142:180–96
Keil RG, Mayer LM. 2014. Mineral matrices and organic matter. In *Treatise on Geochemistry*, Vol. 12: *Organic Geochemistry*, ed. PG Falkowski, KH Freeman, pp. 337–59. Oxford, UK: Elsevier. 2nd ed.
Keil RG, Mayer LM, Quay PD, Richey JE, Hedges JI. 1997. Loss of organic matter from riverine particles in deltas. *Geochem. Cosmochim. Acta* 61:1507–11
Khripounoff A, Crassous P, Lo Bue N, Dennielou B, Silva Jacinto R. 2012. Different types of sediment gravity flows detected in the Var submarine canyon (northwestern Mediterranean Sea). *Prog. Oceanogr.* 106:138–53
Kineke GC, Sternberg RW, Trowbridge JH, Geyer WR. 1996. Fluid-mud processes on the Amazon continental shelf. *Cont. Shelf Res.* 16:667–96
King EL, Haflidason H, Sejrup HP, Lovlie R. 1998. Glacigenic debris flows on the North Sea trough mouth fan during ice stream maxima. *Mar. Geol.* 152:217–46
Kioka A, Schwestermann TC, Moernaut J, Ikehara K, Kanamatsu T, et al. 2019. Megathrust earthquake drives drastic organic carbon supply to the hadal trench. *Sci. Rep.* 9:1553
Kneller B, Buckee C. 2002. The structure and fluid mechanics of turbidity currents: a review of some recent studies and their geological implications. *Sedimentology* 47:62–94
Korup O, Clague JJ, Hermanns RL, Hewit K, Strom A, Weidinger JT. 2007. Giant landslides, topography, and erosion. *Earth Planet. Sci. Lett.* 261:578–89

Kuehl SA, Alexander CR, Blair NE, Harris CK, Marsaglia KM, et al. 2016. A source-to-sink perspective of the Waipaoa River margin. *Earth-Sci. Rev.* 153:301–34

Kuehl SA, Nittrouer CA, Allison MA, Faria LEC, Dukat DA, et al. 1996. Sediment deposition, accumulation, and seabed dynamics in an energetic fine-grained coastal environment. *Cont. Shelf Res.* 16:787–816

Kuenen PH, Migliorini CI. 1950. Turbidity currents as a cause of graded bedding. *J. Geol.* 58:91–127

Lalonde K, Mucci A, Ouellet A, Gélinas Y. 2012. Preservation of organic matter in sediments promoted by iron. *Nature* 483:198–200

Leduc D, Nodder SD, Rowden AA, Gibbs M, Berkenbusch K, et al. 2020. Structure of infaunal communities in New Zealand submarine canyons is linked to origins of sediment organic matter. *Limnol. Oceanogr.* 65:2303–27

Lee H, Galy V, Fend X, Ponton C, Galy A, et al. 2019. Sustained wood burial in the Bengal Fan over the last 19 My. *PNAS* 116:22518–25

Li M, Peng C, He N. 2022. Global patterns of particulate organic carbon export from land to the ocean. *Ecohydrology* 15:e2373

Li Z, Zhang YG, Torres M, Mills BJW. 2023. Neogene burial of organic carbon in the global ocean. *Nature* 613:90–95

Liu JT, Yang RJ, Hsu RT, Kao S-J, Lin H-L, Kuo FH. 2012. Cyclone induced hyperpycnal turbidity currents in a submarine canyon. *J. Geophys. Res.* 117:C04033

Maher BA, Prospero JM, Mackie M, Gaiero D, Hesse PP, Balkanski Y. 2010. Global connections between aeolian dust, climate and ocean biogeochemistry at the present day and at the Last Glacial Maximum. *Earth-Sci. Rev.* 99:61–97

Maier KL, Rosenberger K, Paull CK, Gwiazda R, Gales J, et al. 2019. Sediment and organic carbon transport and deposition driven by internal tides along Monterey Canyon, offshore California. *Deep-Sea Res. I* 153:103108

Mariotti A, Blard PH, Charreau J, Toucanne S, Jorry SJ, et al. 2021. Nonlinear forcing of climate on mountain denudation during glaciations. *Nat. Geosci.* 14:16–22

Maslin M, Vilela C, Mikkelsen N, Grootes P. 2005. Causes of catastrophic sediment failures of the Amazon Fan. *Quat. Sci. Rev.* 24:2180–93

Masson DG, Huvenne VAI, de Stigter HC, Wolff GA, Kiriakoulakis K, et al. 2010. Efficient burial of carbon in a submarine canyon. *Geology* 38:831–34

McArthur AD, Gamberi F, Kneller BC, Wakefield MI, Souza PA, Kuchle J. 2017. Palynofacies classification of submarine fan depositional environments: outcrop examples from the Marnoso-Arenacea Formation, Italy. *Mar. Pet. Geol.* 88:181–99

Middelburg JJ. 2018. Reviews and syntheses: to the bottom of carbon processing at the seafloor. *Biogeosciences* 15:413–27

Milliman JD, Farnsworth KL. 2011. *River Discharge to the Coastal Ocean: A Global Synthesis*. Cambridge, UK: Cambridge Univ. Press

Mountjoy JJ, Howarth JD, Orpin AR, Barnes PM, Bowden DA, et al. 2018. Earthquakes drive large-scale submarine canyon development and sediment supply to deep-ocean basins. *Sci. Adv.* 4:eaar3748

Mulder T, Syvitski JPM, Migneon S, Faugeres JC, Savoye B. 2003. Marine hyperpycnal flows: initiation, behaviour, and related deposits. A review. *Mar. Pet. Geol.* 20:861–82

Nittrouer CA, DeMaster DJ, Kuehl SA, Figueiredo AG Jr., Sternberg RW, et al. 2021. Amazon sediment transport and accumulation along the continuum of mixed fluvial and marine processes. *Annu. Rev. Mar. Sci.* 13:501–36

Normandeau A, Bourgault D, Neumeier U, Lajeunesse P, St-Onge G, et al. 2020. Storm-induced turbidity currents on a sediment-starved shelf: insight from direct monitoring and repeat seabed mapping of upslope migrating bedforms. *Sedimentology* 67:1045–68

Normark WB, Meyer AH, Cremer M, Droz L, O'Connell S, et al. 1986. Summary of drilling results for the Mississippi Fan and considerations for applications to other turbidite systems. In *Initial Reports of the Deep Sea Drilling Project*, Vol. 96, ed. AH Bouma, JM Coleman, J Brooks, WR Bryant, R Constans, et al., pp. 425–36. Washington, DC: US Gov. Print. Off.

Nygård A, Sejrup HP, Haflidason H, Lekens WAH, Clark C, Bigg R. 2007. Extreme sediment and ice discharge from marine-based ice streams; new evidence from the North Sea. *Geology* 35:395–98

Paradis S, Arjona-Camas M, Goni M, Palanques A, Masque P, Puig P. 2022. Contrasting particle fluxes and composition in a submarine canyon affected by natural sediment transport events and bottom trawling. *Front. Mar. Sci.* 9:1017052

Paull CK, Talling PJ, Maier K, Parsons D, Xu J, et al. 2018. Powerful turbidity currents driven by dense basal layers. *Nat. Commun.* 9:4144

Paull CK, Ussler W, Mitts PJ, Caress DW, West GJ. 2006. Discordant ^{14}C-stratigraphies in upper Monterey Canyon: a signal of anthropogenic disturbance. *Mar. Geol.* 233:21–36

Payo-Payo M, Silva Jacinto R, Lastras G, Rabineau M, Puig P, et al. 2017. Numerical modeling of bottom trawling-induced sediment transport and accumulation in La Fonera submarine canyon, northwestern Mediterranean Sea. *Mar. Geol.* 386:107–25

Picot M, Droz L, Marsset T, Dennielou B, Bez M. 2015. Controls on turbidite sedimentation: insights from a quantitative approach of submarine channel and lobe architecture (Late Quaternary Congo Fan). *Mar. Pet. Geol.* 72:423–46

Piper DJW, Cochonat P, Morrison ML. 1999. The sequence of events around the epicentre of the 1929 Grand Banks earthquake: initiation of debris flows and turbidity current inferred from sidescan sonar. *Sedimentology* 46:79–97

Piper DJW, Flood RD, Cisowski C, Hall F, Manley PL, et al. 1997. Synthesis of stratigraphic correlations of the Amazon fan. In *Proceedings of the Ocean Drilling Program: Scientific Results*, Vol. 155, ed. RD Flood, DJW Piper, A Klaus, LC Peterson, pp. 595–610. College Station, TX: Ocean Drill. Program

Plank T, Manning CE. 2019. Subducting carbon. *Nature* 574:343–52

Pope EL, Cartigny MJB, Clare MA, Talling PJ, Lintern DG, et al. 2022. First source-to-sink monitoring shows dense head determines sediment gravity flow runout. *Sci. Adv.* 8:eabj3220

Pope EL, Normandeau A, Ó Cofaigh C, Stokes CR, Talling PJ. 2019. Controls on the formation of turbidity current channels associated with marine-terminating glaciers and ice sheets. *Mar. Geol.* 45:105951

Posamentier HW, Kolla V. 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *J. Sediment. Res.* 73:367–88

Prahl FG, Ertel JR, Goni MA, Sparrow MA, Eversmeyer B. 1994. Terrestrial organic carbon contributions to sediments on the Washington margin. *Geochim. Cosmochim. Acta* 58:3035–48

Pratson L, Nittrouer C, Wiberg P, Steckler M, Swenson J, et al. 2009. Seascape evolution on clastic continental shelves and slopes. In *Continental Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy*, ed. CA Nittrouer, JA Austin, ME Field, JH Kravitz, JPM Syvitski, PL Wiberg, pp. 339–73. Malden, MA: Blackwell

Puig P, Canals M, Company JB, Martín J, Amblas D, et al. 2012. Ploughing the deep sea floor. *Nature* 489:286–89

Quadfasel D, Kudrass H, Frische A. 1990. Deep-water renewal by turbidity currents in the Sulu Sea. *Nature* 348:320–22

Rabouille C, Baudin F, Dennielou B, Olu K. 2017. Organic carbon transfer and ecosystem functioning in terminal lobes of Congo deep-sea fan: outcomes of the Conglobe project. *Deep-Sea Res. II* 142:1–6

Rabouille C, Dennielou B, Baudin F, Raimonet M, Droz L, et al. 2019. Carbon and silica megasink in deep-sea sediments of the Congo terminal lobes. *Quat. Sci. Rev.* 222:105854

Raiswell R, Benning LG, Tranter M, Tulaczyk S. 2008. Bioavailable iron in the Southern Ocean: the significance of the iceberg conveyor belt. *Geochem. Trans.* 9:1189–87

Regard V, Premaillon M, Dewez TJB, Carretier S, Jeandel C, et al. 2022. Rock coast erosion: an overlooked source of sediments to the ocean. Europe as an example. *Earth Planet. Sci. Lett.* 579:117356

Regnier P, Resplandy L, Najjar RG, Ciais P. 2022. The land-to-ocean loops of the global carbon cycle. *Nature* 603:401–10

Repasch M, Scheingross JS, Hovius N, Vieth-Hillebrand A, Mueller CW, et al. 2022. River organic carbon fluxes modulated by hydrodynamic sorting of particulate organic matter. *Geophys. Res. Lett.* 49:e2021GL096343

Rogers KG, Goodbred S. 2010. Mass failures associated with the passage of a large tropical cyclone over the Swatch of No Ground submarine canyon (Bay of Bengal). *Geology* 38:1051–54

Saller A, Lin R, Dunham J. 2006. Leaves in turbidite sands: the main source of oil and gas in the deep-water Kutei Basin, Indonesia. *AAPG Bull.* 90:1585–608

Sampere TP, Bianchi TS, Wakeham SG, Allison MA. 2008. Sources of organic matter in surface sediments of the Louisiana Continental Margin: effects of primary depositional/transport pathways and a hurricane event. *Cont. Shelf Res.* 28:2472–87
Schlünz B, Schneider RR. 2000. Transport of terrestrial organic carbon to the oceans by rivers: re-estimating flux and burial rates. *Int. J. Earth Sci.* 88:599–606
Schlünz B, Schneider RR, Müller PJ, Showers J, Wefer G. 1999. Terrestrial organic carbon accumulation on the Amazon deep sea fan during the last glacial sea level low stand. *Chem. Geol.* 159:263–81
Schwab MS, Hilton RG, Haghipour N, Baronas JJ, Eglinton TI. 2022. Vegetal undercurrents—obscured riverine dynamics of plant debris. *J. Geophys. Res.* 127:e2021JG006726
Shang H. 2023. A generic hierarchical model of organic matter degradation and preservation in aquatic systems. *Commun. Earth Environ.* 4:16
Sigman D, Boyle E. 2000. Glacial/interglacial variations in atmospheric carbon dioxide. *Nature* 407:859–69
Simmons SM, Azpiroz-Zabala M, Cartigny MJB, Clare MA, Cooper C, et al. 2020. Novel acoustic method provides first detailed measurements of sediment concentration structure within submarine turbidity currents. *J. Geophys. Res.* 125:e2019JC015904
Smeaton C, Austin WEN. 2022. Understanding the role of terrestrial and marine carbon in the mid-latitude fjords of Scotland. *Glob. Biogeochem. Cycles* 36:e2022GB007434
Smith R, Bianchi T, Allison M, Savage C. 2015. High rates of organic carbon burial in fjord sediments globally. *Nat. Geosci.* 8:450–53
Sternberg RW, Cacchione DA, Paulson B, Kineke GC, Drake DE. 1996. Observations of sediment transport on the Amazon subaqueous delta. *Cont. Shelf Res.* 16:697–715
Stetten E, Baudin F, Reyss JL, Martinez P, Charlier K, et al. 2015. Organic matter characterization and distribution in sediments of the terminal lobes of the Congo deep-sea fan: evidence for the direct influence of the Congo River. *Mar. Geol.* 369:182–95
Sundquist ET. 1993. The global carbon dioxide budget. *Science* 259:934–41
Sundquist ET, Visser K. 2004. The geologic history of the carbon cycle. In *Treatise on Geochemistry*, Vol. 8: *Biogeochemistry*, ed. WH Schlesinger, pp. 425–72. Amsterdam: Elsevier
Syvitski J, Angel JR, Saito Y, Overeem I, Vörösmarty CJ, et al. 2022. Earth's sediment cycle during the Anthropocene. *Nat. Rev. Earth Environ.* 3:179–96
Talling PJ. 2014. On the triggers, resulting flow types and frequency of subaqueous sediment density flows in different settings. *Mar. Geol.* 352:155–82
Talling PJ, Allin J, Armitage DA, Arnott RWC, Cartigny MJB, et al. 2015. Key future directions for research on turbidity currents and their deposits. *J. Sediment. Res.* 85:153–69
Talling PJ, Amy LA, Wynn RB, Peakall J, Robinson M. 2004. Beds comprising debrite sandwiched within co-genetic turbidite: origin and widespread occurrence in distal depositional environments. *Sedimentology* 51:163–94
Talling PJ, Baker ML, Pope EL, Ruffell SC, Silva Jacinto R, et al. 2022. Longest sediment flows yet measured show how major rivers connect efficiently to deep sea. *Nat. Commun.* 13:4193
Talling PJ, Clare M, Urlaub M, Pope E, Hunt JE, Watt SL. 2014. Large submarine landslides on continental slopes: geohazards and role in methane release and climate change. *Oceanography* 27(2):32–45
Talling PJ, Sumner EJ, Masson DG, Malgesini G. 2012. Subaqueous sediment density flows: depositional processes and deposit types. *Sedimentology* 59:1937–2003
Talling PJ, Wynn RB, Masson DG, Frenz M, Cronin BT, et al. 2007. Onset of submarine debris flow deposition far from original giant landslide. *Nature* 450:541–44
Thomson J, Colley S, Higgs NC, Hydes DJ, Wilson TRS, Sorensen J. 1987. Geochemical oxidation fronts in NE Atlantic distal turbidites and their effects in the sedimentary record. In *Geology and Geochemistry of Abyssal Plains*, ed. PPE Weaver, J Thomson, pp. 167–77. Geol. Soc. Spec. Publ. 31. London: Geol. Soc.
Torres MA, West AJ, Li G. 2014. Sulphide oxidation and carbonate dissolution as a source of CO_2 over geological timescales. *Nature* 507:346–49
Vale NF, Braga JC, de Moura RL, Salgado LT, de Moraes FC, et al. 2022. Distribution, morphology and composition of mesophotic 'reefs' on the Amazon Continental Margin. *Mar. Geol.* 447:106779
Wadham JL, Hawkings JR, Tarasov L, Gregoire LJ, Spencer RGM, et al. 2019. Ice sheets matter for the global carbon cycle. *Nat. Commun.* 10:3567

Walsh JP, Nittrouer CA. 2009. Understanding fine-grained river-sediment dispersal on continental margins. *Mar. Geol.* 263:34–45

Wright LD, Friedrichs CT. 2006. Gravity-driven sediment transport on continental shelves: a status report. *Cont. Shelf Res.* 26:2092–107

Xu B, Bianchi TS, Allison MA, Dimova NT, Wang H, et al. 2015. Using multi-radiotracer technique to evaluate sedimentary dynamics of reworked muds in the Changjiang River and estuary and East China Sea. *Mar. Geol.* 370:78–86

Zeng N. 2003. Glacial-interglacial atmospheric CO_2 change—the glacial burial hypothesis. *Adv. Atmos. Sci.* 20:677–93

Zeng N. 2007. Quasi-100 ky glacial-interglacial cycles triggered by subglacial burial carbon release. *Clim. Past* 3:135–53

Zhao B, Yao P, Bianchi TS, Wang X, Shields MR, et al. 2023. Dynamics of iron-associated organic carbon in the Changjiang Estuary. *Geochim. Cosmochim. Acta* 345:39–49

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Contents

Errata

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