Detailed monitoring reveals the nature of submarine turbidity currents

Peter J. Talling[1†], Matthieu J.B. Cartigny[2], Ed Pope[2], Megan Baker[2], Michael A. Clare[3], Maarten Heijnen[4], Sophie Hage[5], Dan R. Parsons[6], Steve M. Simmons[6], Charlie K. Paull[7], Roberto Gwiazda[7], Gwyn Lintern[8], John E. Hughes Clarke[9], Jingping Xu[10], Ricardo Silva Jacinto[5], and Katherine L. Maier[11]

1. Departments of Geography and Earth Sciences, University of Durham, Durham, U.K.
2. Department of Geography, University of Durham, Durham, U.K.
3. Ocean BioGeosciences Group, National Oceanography Centre, Southampton, U.K.
4. School of Ocean and Earth Sciences, University of Southampton, Southampton, U.K.
5. Geo-Ocean, University of Brest, CNRS, IFREMER, Plouzané, France.
6. Energy and Environment Institute, University of Hull, Hull, U.K.
7. Monterey Bay Aquarium Research Institute, Moss Landing, CA, U.S.A.
8. Geological Survey of Canada, Natural Resources Canada, Sidney, BC, Canada.
9. University of New Hampshire, Durham, NH, U.S.A.
10. Southern University of Science and Technology, Guangdong, China.
11. National Institute of Water and Atmospheric Research, Te Whanganui-a-Tara Wellington, Aotearoa New Zealand.

[†]Email: Peter.J.Talling@durham.ac.uk

Abstract

Seafloor sediment flows, called turbidity currents, form the largest sediment accumulations, deepest canyons, and longest channels on Earth. It was once thought that turbidity currents were impractical to measure in action, especially due to their ability to damage sensors in their path, but direct monitoring since the mid 2010s has measured them in detail. In this Review, we summarise knowledge of turbidity currents gleaned from this direct monitoring. Monitoring identifies triggering mechanisms from dilute river-plumes, and shows how rapid sediment accumulation can precondition slope failure, but the final triggers can be delayed and subtle. Turbidity currents are consistently more frequent than predicted by past sequence stratigraphic models, including at sites >300 km from any coast. Faster ($>\sim 1.5$ m s^{-1}) flows are driven by a dense near-bed layer at their front, whereas slower flows are entirely dilute. This frontal layer sometimes erodes large (>2.5 km^3) volumes of sediment, yet maintains a near-uniform speed, leading to a travelling wave model. Monitoring shows that flows sculpt canyons and channels through fast-moving knickpoints, and how deposits originate.

Emerging technologies with reduced cost and risk can lead to widespread monitoring of turbidity currents, so their sediment and carbon fluxes can be compared with other major global transport processes.

[H1] Introduction

Turbidity currents **[G]** are mixtures of sediment and water that travel downslope because they are denser than the surrounding water[1]. These currents can have prodigious scale and power[2-7] (**Fig. 1; Supplementary Table 1**). For example, a turbidity current in 1929 broke all of the telecommunication cables across the NW Atlantic and had a sediment volume of approximately 200 km^3 (ref.[2,3]), which is ~30 times larger than the global annual sediment flux from rivers, and exceeds that of the largest subaerial landslide (~50 km^3) in the last 350,000 years (**Fig 1b; Supplementary Table 1**). These cable breaks showed that the 1929 flow travelled at speeds of up to 19 m s^{-1} and ranout for over 800 km (ref.[2,3]) (**Fig. 1a**). Additionally, in 2020, turbidity currents that initiated at the mouth of the Congo River travelled >1,100 km through the Congo Submarine Canyon offshore West Africa[4] (**Fig. 1a**), accelerating from 5 to 8 m s^{-1} and eroding ~2.65 km^3 of sediment (**Fig. 1b**). These 2020 flows broke both seabed telecommunication cables to West Africa, causing the internet to slow from Nigeria to South Africa, just when capacity was most needed during Covid-19 related lockdowns[4,5].

Turbidity currents are important for many reasons. As shown by the 1929 NW Atlantic and 2020 Congo Canyon flows, turbidity currents commonly break networks of seabed telecommunication cables[2-7] that now carry over 99% of global intercontinental data traffic, as they have much larger bandwidth than satellites[7]. These cables form the backbone of the internet, and are critical for many aspects of daily life, from intercontinental phone traffic to financial markets and cloud data storage[7]. Turbidity currents also have an important role in the transfer and burial of fresh organic carbon in marine sediments, which remove CO_2 from the atmosphere, regulating climate over geological time scales[8-10] (**Fig. 2**). It was once thought that terrestrial organic carbon supplied to the oceans was mainly oxidized on continental shelves[11-13], and turbidity currents were omitted from analyses of global carbon cycles[11-13]. However, the burial of terrestrial organic carbon through turbidity currents can be highly efficient[8,9], and global estimates of organic carbon burial in marine sediments might thus need to be revisited[14] (**Fig. 2b**). Organic carbon is also the basis for all non-chemosynthetic marine food webs, and turbidity currents could thus have a key role in determining how seabed ecosystems function[15,16]. For example, rapid and sustained deposition of organic-carbon-rich sediment by turbidity currents can favour chemosynthetic communities[16], whilst extremely powerful flows can sometimes scour life from the seafloor[5,17].

Turbidity currents and their carbon transport are linked to human activities, as they can be generated by seabed trawling[18]. These flows also transfer microplastics and other pollutants generated by human activities into the deep-sea[19]. Additionally, turbidity current deposits (called turbidites **[G]**) can provide a record of Earth history, including long-term and therefore valuable records of other important geohazards such as major earthquakes[20-22], or river-floods[4]; although it can be very challenging to infer the triggering mechanism for an ancient turbidite with confidence. Thick and extensive turbidite deposits in the rock record also host major oil and gas reserves in many locations worldwide[23]. Major advances in understanding have previously been made using analyses of rock outcrops, seabed cores, and turbidity currents within laboratory experiments or numerical models[1,24-26].

Perhaps the most remarkable aspect of submarine turbidity currents is how few direct measurements of these flows were previously available [27-31], ensuring that they were poorly understood[32]. Indeed, it was once thought to be impractical[33] to measure turbidity currents directly in the oceans, owing to their location, infrequent occurrence, and ability to badly damage (or entirely remove) sensors in their path. However, since the mid 2010s, a series of ambitious projects have used new sensors and methods to provide the first detailed measurements within submarine turbidity currents (**Fig. 3**). For example, these projects consistently use acoustic Doppler current profilers **[G]** (ADCPs) mounted on moorings (**Fig. 3e**) to measure flow velocity profiles at frequencies of seconds to minutes, including at multiple places along the flow pathway[34-53]. ADCPs emit a sound-pulse that is scattered from sand and mud particles within a turbidity current and measure the speed of those particles at different heights above the seabed to produce a velocity profile. Projects were initially conducted in shallow (< 500 m) water[38,39], where logistics are easier and costs lower, before moving into deeper (up to 2 km) water[35-37], and then finally capturing extremely large events that reach depths of 4–5 km (ref.[4]) (**Fig. 3b-d**). Direct flow monitoring has been combined with detailed time-lapse mapping of the seabed[35,38,39,54], tracking of heavy objects[35,53] (**Fig.**

3f), sediment traps inside the flow[41-42,51], and coring of seabed deposits[50,51] to advance understanding of how turbidity currents work. These projects have not been without challenges and risks, such as needing to recover broken moorings drifting across the ocean surface near the Congo Canyon before their locator beacons stopped transmitting, all during a Covid-19 related lockdown[4,5], finding and recovering severed and buried cabled infrastructure[48], or when turbidity currents occurred only on the last days of field campaigns[50].

In this Review, we outline how direct monitoring can address fundamental questions about turbidity currents including how turbidity currents are caused, and how reliably they record other major geohazards for example earthquakes or floods; how frequently turbidity currents occur, and the wider implications for organic carbon cycles **(Fig. 2)**; what the internal composition of turbidity currents is and whether they are entirely dilute suspensions or driven by dense near-bed layers; how flows evolve and behave; how flows sculpt the seafloor; and how turbidity currents are recorded by their deposits. Finally, we outline some key challenges for future research in this field, including the importance of reducing the cost and risk associated with direct measurements of turbidity currents.

[H1] Causes of turbidity currents

This section outlines how turbidity currents are generated, which can be through four general types of processes[55,56] (**Fig. 4a**). First, turbidity currents can form from the disintegration of underwater landslides[3,55,56,57] that can have a variety of preconditioning factors (such as, rapid sediment accumulation) and final triggers (such as, earthquakes or repeated wave loading). Second, turbidity currents can originate from sediment-laden river discharge that is denser than seawater, and thus plunges to move along the seabed as a ‘hyperpycnal flow’[58], although such conditions are rare. Third, sediment settling from surface river plumes with much lower sediment concentrations than hyperpycnal flows could generate turbidity currents[39,58]. Fourth, turbidity currents can be initiated by oceanographic processes such as storm waves and tides, or internal waves that move along density waves within the ocean that transfer sediment to canyon heads, which might be located far from river mouths[27,55,56].

It was previously thought that surface river plumes could only generate turbidity currents when sediment concentrations in rivers exceeded 1 kg m^{-3}. However, direct measurements of sediment concentrations in rivers and monitoring of turbidity currents at Squamish Delta (Canada) showed that surface river plumes with sediment concentrations as low as 0.07 kg m^{-3} can generate turbidity currents[39], sometimes even more frequently than landslide-triggered turbidity currents[59]. Therefore, a much larger fraction of global river mouths have the potential to generate turbidity currents than was once thought[39]. The exact mechanism by which turbidity currents originate from below such dilute surface plumes is still uncertain, but it could be linked to the generation of mobile fluid-mud-like layers on the seabed[39,47,48], or sediment trapping through estuarine circulation, or both[39].

Direct monitoring also shows that in many locations turbidity currents are caused by a combination of river floods and tidal cycles (**Fig. 4b-d**), representing both riverine and oceanographic processes. For example, at both Squamish Delta and nearby Fraser Delta in British Columbia, Canada, turbidity currents tend to occur at spring low tides, when river discharge exceeds a threshold value[38,39,47,48]. The timing of extremely large turbidity currents in Congo Canyon offshore West Africa in 2020–2021 shows they are also associated with a combination of major (1-in-50-year) river floods and spring tides (**Fig. 4c**).

However, there might be a significant time delay between a river flood peak, and the eventual final trigger of a turbidity current. For example, the very large turbidity currents in the Congo Canyon occurred several weeks to months after the Congo River's flood peak, typically at spring tides[4] (**Fig. 4c**). A similar pattern is seen elsewhere, albeit with shorter delays. A turbidity current occurred 2–3 days after a huge flood along the Gaoping River in Taiwan[6], although in this case the final trigger was not a spring tide, whereas landslide-triggered turbidity currents occurred hours after the flood peak at the Squamish Delta[60]. Therefore, it appears that submarine canyon **[G]** heads store sediment (acting as a capacitor), which is later discharged, often owing to a minor external perturbation, such as spring tides and other mechanisms[4,60,61] (**Fig. 4d**). Such time delays complicate the relationship between the timing of major external events (such as, floods and earthquakes) and turbidity currents. Indeed, in a few cases, direct measurements show that turbidity currents can be triggered without any obvious synchronous external trigger. For example, a turbidity current that moved at 4–7 m s^{-1} and ran out for 50 km in Monterey Canyon occurred on a day without a storm, river flood or earthquake[61].

It is important to understand the triggers of canyon-flushing turbidity currents because it has been proposed that deep-sea turbidites can record major earthquakes in some settings. If reliable, turbidite paleo-seismology would be valuable, as these marine records go back further in time than almost all land-based records[20-22]. However, care is needed as there are potential pitfalls. Earthquake triggered turbidites need to be reliably distinguished from turbidites triggered in other ways, and it is important to test whether all (or only some) major earthquakes trigger distinctive turbidity currents[21,22]. It has been proposed that earthquakes are the only events to produce synchronous turbidites (layers of sand and mud) over very extensive (>100 km) areas[20]. However, it is difficult to correlate individual turbidite layers over such distances, especially for ancient layers if the uncertainties in radiocarbon dates are similar to the earthquake recurrence intervals[20,22]. Turbidite layers could also be emplaced due to tropical cyclones that affect areas comparable to those of major earthquakes[22]. Turbidites with multiple fining-upward cycles of grain size have been linked to peaks in ground motion during earthquakes[20], but turbidity currents with multiple pulses can also be generated by river floods[36,37,46]. Repeated shaking owing to earthquakes could also potentially cause sediment to consolidate and become stronger in some locations[62]. Despite these challenges, substantial advances have been made in assessing the reliability of the identification of earthquake triggered turbidites, and understanding which sites are better suited for turbidite paleoseismology. For example, there was a consistent spatial relationship between earthquake induced ground motion during the 2016 Kaikōura earthquake and coseismic turbidites[21]. Additionally, the moment magnitude (M_w) 9 Tohoku-Oki earthquake offshore Japan in 2011 remobilised a layer of surface sediment that was just a few centimeters thick over a large area where ground motion was strongest[63]. Turbidites that are precisely dated using varves **[G]** in lakes can be correlated with confidence and provide compelling evidence for earthquake triggering[64].

Direct monitoring can also test how turbidity currents can record major river floods[46,58]. For example, a single flood from the Congo River produced a cluster of multiple offshore turbidity currents in the following years[4] (**Fig. 4c**). Direct monitoring of the Var system in the Mediterranean revealed that (non-earthquake) landslides and floods produced turbidity currents with multiple pulses; therefore, multi-pulsed deposits are not a unique criterion for identifying earthquake or flood triggering[46]. Finally, turbidites can also provide important insights into how volcanic islands collapse[65], and whether this collapse occurs in one or multiple stages, which is critically important for assessing the tsunami magnitude.

[H1] Flow frequency

This section outlines insights into the frequency of turbidity currents, and some of their wider implications, such as for the transfer and burial of organic carbon or seabed life. Direct monitoring of turbidity currents has consistently found that turbidity currents are more frequent than previously predicted (**Fig. 5; Supplementary Fig. 1**), such as by sequence stratigraphic models[66] (**Fig. 5c,d**). These sequence stratigraphic models infer that most modern turbidity current systems are inactive, with activity being mainly restricted to periods of falling or low global sea-level[66] (**Fig. 5c**). This reduced turbidity current activity is because post-glacial sea-level rise has flooded continental shelves, ensuring that almost all modern-day submarine canyon-heads are detached from river mouths (**Fig. 5**), with only ~180 of ~9,500 submarine canyons currently extending to within 6 km of shore[67,68].

However, direct monitoring now shows that modern-day turbidity current systems can be highly active in a range of settings (**Supplementary Fig. 1)**. For example, over 100 turbidity currents occurred on Squamish Pro-delta in Canada in ~3 months (ref.[38,39,59,60]), and turbidity currents in the upper Congo Canyon can last for over a week and are active ~30% of the time[36,37]. Turbidity currents have even been observed in canyons fed by rocky shorelines that lack obvious sediment sources[43]. Powerful canyon-flushing turbidity currents might also be more frequent than once thought, as they can be linked to river floods with recurrence intervals of a few decades[4] (**Fig. 4c**), as well as major earthquakes with longer recurrence intervals[17]. Frequent and powerful flows have also been measured outside of submarine canyons and channels. For example, dozens of flows occurred on the open-slope of the Fraser Pro-delta, some with velocities of >6 m s^{-1} (ref.[47,48]). Most surprisingly, 4–6 powerful (5–8 m s^{-1}) flows occurred in Whittard Canyon during 14 months from June 2019 to August 2020, despite this canyon being >300 km from the nearest shoreline[69] (**Supplementary Fig. 1a-c**). Indeed, turbidity currents are as frequent in Whittard Canyon in the N.E. Atlantic as Monterey Canyon in California, whose head is located tens of meters from the shoreline[15,35]. There are several thousand other shoreline-detached canyons similar to Whittard Canyon[67,68], and these findings raise the question of what their flow activity might be[69].

These findings from direct monitoring are consistent with those from previous approaches based on dated turbidites on sediment cores that challenged the prevailing models of dormant turbidity current systems during sea-level high-stands[70] (**Fig. 5c,d**). Other lines of evidence than direct monitoring also suggested that turbidity currents could efficiently transfer sediment to the deep-sea, even when submarine canyon heads are not located within a few kilometers of river mouths (**Fig. 5e**). Prograding wedges of sediment (clinoforms) offshore from major rivers can reach canyon heads (**Fig. 5e**). For example, the Ganges-Brahmaputra River, which supplies ~16% of all riverine sediment to the ocean[71], is highly active despite having a submarine canyon-head 130 km from the river mouth, owing to the presence of a clinoform on the shelf[72]. Oceanographic processes are likely to have a key role in producing these highly active turbidity current systems located far from river mouths. For example, waves and tides can resuspend sediment and efficiently transport it across continental shelves to submarine canyons[73], such as, in the continental shelf offshore from the Eel River where 70–80% of sediment was lost over the shelf edge[74].

[H1] Implications for carbon transport

The present turbidity current pump might be much more active than previously thought (**Fig. 2**), which could have important implications for the transfer and burial of organic carbon in the deep-sea[8,14], which affects atmospheric CO_2 levels and thus climate over long (>1,000 year) time scales[8,10,13,14]. Previous analyses of global carbon burial in the oceans have largely neglected the role of turbidity currents, assuming that terrestrial organic carbon supplied by rivers is buried almost exclusively within deltas or continental shelves[11,12]. Additionally, these analyses assumed that there was remineralization **[G]** of most terrestrial organic carbon on the continental shelves, leading to the release of CO_2, as occurs offshore from the Amazon River[11,12, 75], such that the global burial efficiency of terrestrial organic carbon in marine sediments was low[11-13] (10–44%).

However, comparisons of organic carbon types in major rivers and deep-sea submarine fan **[G]** turbidites suggest that terrestrial organic carbon burial by turbidity currents can be highly efficient (>60–100%) in settings ranging from the exceptionally large Bengal Fan[8] (**Fig. 2d**), to fjords[76], and systems fed by small mountainous rivers in Oceania[9]. These findings led to revised global estimates of the mass-flux (~62–90 MtC yr^{-1}) and efficiency (31–45%) of terrestrial organic carbon burial in marine sediments[14]. Photosynthesis in the ocean surface produces organic carbon at a very fast rate[77] (50,000 MtC yr^{-1}), but only 90–130 MtC yr^{-1} of that marine carbon is buried at the seabed[10-14,77] (**Fig. 2b**). Thus, the burial flux of terrestrial organic carbon by turbidity currents is close to that caused by the settling of marine carbon from the ocean surface[14]. However, only the production of marine carbon through photosynthesis in the ocean surface will affect the atmospheric partial pressure of CO_2 (pCO_2) and thus the climate on short (<100 yr) time scales[78] (**Fig. 2c**).

During glacial low-stands almost all rivers would be directly connected to a submarine canyon[67,68], increasing the efficiency of terrestrial organic carbon burial in the oceans from ~31–45% to >60–80% (ref.[14]). Therefore, it is possible that the rate of terrestrial organic carbon burial by turbidity currents varies systematically and substantially throughout glacial–interglacial cycles[79]. It is often inferred that during glacial periods increases in surface ocean productivity further reduced atmospheric pCO_2 levels[78]. However, increases in the efficiency of terrestrial organic carbon burial by turbidity currents could also act as a positive feedback to reduce atmospheric pCO_2 levels during glacial low-stands, albeit over much longer (>1,000 years) timescales than changes in surface ocean productivity[79]. Thus, the magnitude of the difference in the turbidity current organic carbon burial flux between glacial and inter-glacial periods (~30–95 Mt yr^{-1}) could be comparable with changes in the rate of global organic carbon burial that are proposed to drive other longer-term climate fluctuations[14]. For example, a comparable reduction in the global organic carbon burial flux (~90 Mt yr^{-1}) was an important positive feedback for driving global warming during the Neogene[80].

A more active turbidity current carbon pump could also have important implications for seabed life, as organic carbon underpins most marine food webs[81,82]. Additionally, turbidity currents can physically disturb ecosystems by scouring the seabed, sometimes to depths of tens of meters, or by depositing thick sediment layers that smother ecosystems[17]. The rapid accumulation of sediment rich in organic matter can also lead to the formation of chemotrophic ecosystems resembling those that are present around black smokers[82]. Thus, the impacts of turbidity currents on marine life warrant further analysis.

Monitoring projects have also revealed that human activities might trigger turbidity currents, and thus impact wide areas of the seafloor. For example, bottom trawling can both smooth (plough) the seabed, and initiate turbidity currents that travel down canyons[18]. This canyon-monitoring work built upon previous, remarkably determined, efforts to record how cold and dense water masses formed on continental shelves can cascade down submarine canyons[83]. It took almost a decade of research cruises to record these strong dense water cascades in action, but it showed how direct measurements can lead to major advances[83]. Turbidity currents can also disperse microplastics and other pollutants[19], or ventilate the deep ocean with warm, oxygenated water[84].

[H1] The internal composition of turbidity currents

This section uses direct monitoring observations to understand the internal structure and composition of turbidity currents. There has long been controversy over what turbidity currents comprise[1,26,85-86]. This debate centres on whether turbidity currents are entirely dilute and fully turbulent sediment suspensions, as for most rivers, or driven by dense near-bed layers that resemble debris flows[1,26,85-86]. This debate is not just a minor detail; it is critical because the physics of dense or dilute sediment flows are very different, and it is important to know which type of flow to model in the laboratory or numerically[86]. Geologists tried to answer this question by examining turbidite deposits; however, the findings are often unclear, especially when the deposits comprise massive or planar laminated sand[86].

Detailed measurements within turbidity currents, such as from ADCPs, have a key role in understanding their internal nature (**Fig. 6**). Such measurements reveal that the velocity structure of turbidity currents can differ substantially from laboratory experiments, where a fast-moving body feeds a slow-moving head[33] (**Fig. 6b)**. Measurements from the Congo Canyon show that turbidity currents instead comprise a fast-moving frontal zone (frontal cell **[G]**) that outruns a much slower-moving body, leading to flow stretching[36,37] (**Fig. 6a,b**). Such stretching could explain the surprising week-long duration of flows in the Congo Canyon flows (**Fig. 6a**). Elsewhere, sand-dominated turbidity currents also display a short-lived (<30 min) frontal cell where velocities are fastest (**Fig. 6c**), but these flows only lasted for minutes to hours[34,35,41,45,46,50,53] (**Fig. 6c; Supplementary Fig. 1d**). These flows lacked the sustained week-long body seen in Congo Canyon flows, presumably because Congo Canyon flows contain more mud, which settles slower than sand[36,37].

There is also mounting evidence that fast (>1.5 m s^{-1}) turbidity currents contain dense near-bed layers at their front, which drive the flow[35,38,40] (**Fig. 6**). Multibeam echosounders observed dense near-bed layers in fast-moving (>1.5 m s^{-1}) flows at Squamish Delta[38]; however, the exact sediment concentration of these layers is unknown. Transit (flow front) velocities derived from flow arrival times at ADCP-moorings in Monterey Canyon were quicker than the maximum velocities measured by ADCPs inside the flow[35]. This finding was initially puzzling, as the flow front must push through surrounding seawater that retards its progress. However, ADCPs typically do not measure the flow within a few meters of the bed, suggesting that there could be a thin and fast layer near the bed[35]. Even more surprisingly, very heavy (up to 800 kg), dense (up to 6 g $\mathrm{cm^{-3}}$) and irregularly shaped objects (**Fig. 3f**) were carried several kilometres down Monterey Canyon at speeds of up to 4 m $\mathrm{s^{-1}}$, comparable to the maximum flow speeds[35, 52]. These objects had different masses, densities and shapes, yet sometimes moved synchronously together[35, 52]. In this case it appears that the dense near-bed layers entombed and rafted the heavy objects. This conclusion is supported by measurements from a conductivity probe that recorded high sediment volume concentrations of >11% close to the bed[49].

The Chezy equation can be used to predict vertically-averaged sediment concentrations using independently measured flow velocities and thicknesses, and a friction coefficient (**Fig. 6c-e**). This equation was applied to turbidity currents in Bute Inlet (Canada), showing that fast (>1.5 m $\mathrm{s^{-1}}$) flows are relatively dense (with volume concentrations of >10% and up to 38% sediment volume; **Fig. 6c**), whereas slower moving flows are entirely dilute[40] (**Fig. 6e**). The dense parts of the flows carry most of the sediment and drive the overall event[40], and they are likely to be characterised by strongly damped turbulence and hindered settling, as well as grain-to-grain interactions. There is additional evidence to support the view that slow moving flows are entirely dilute (**Fig. 6e**). For example, acoustic backscatter measurements from ADCPs can be used to derive sediment concentrations, after making some assumptions about grain sizes[36, 37]. This method concludes that in the Congo Canyon the overlying sediment cloud and trailing body (**Fig. 6a**) typically has sediment concentrations of just 0.1 to 0.001% by volume[37].

Field evidence also supports the idea that flows could evolve from having a dense near-bed layer to become entirely dilute and fully turbulent as they decelerate[35,40]. For example, dense near-bed layers were not observed by multibeam sonars in slow flows at Squamish Delta[38], and objects were not carried for such long distances at distal sites in Monterey Canyon[35]. Additionally, analyses using the Chezy-equation demonstrated that flows can evolve from having a dense frontal layer to being entirely dilute as they decelerate[40] (**Fig. 6c-e**).

[H1] Behaviour of turbidity currents

This section seeks to understand the spatial and temporal evolution of turbidity currents, and thus how they behave. Submarine turbidity currents have some similarities to terrestrial river systems, such as the way they can both produce meandering channels; however, their behaviour differs in some fundamental regards[24]. Unlike rivers, turbidity currents are driven by the weight of the sediment that they carry, and density differences with the surrounding seawater. There are three basic hypotheses that describe the behaviour of turbidity currents (**Fig. 7**). First, the deposition of sediment can reduce the density and thus velocity of the flow, leading to further sediment settling, and consequently flow dissipation **[G]** (**Fig. 7a**). Second, turbidity currents that erode the seabed can increase in density and speed, as more sediment is incorporated into the flow, causing even more erosion and acceleration, producing a positive feedback effect known as ignition **[G]**[25] (**Fig. 7b**). Last, the rate of erosion and deposition of sediment could be balanced, such that turbidity currents maintain a uniform velocity and near equilibrium state termed autosuspension **[G]**[4, 25] (**Fig. 7c**).

Direct monitoring measurements can be used to test these hypotheses. Detailed information on the spatial changes in the speed of the flow front is only available for a handful of sites, but these datasets show a remarkably consistent pattern[4,40,87] (**Fig. 7d**). Flow behaviour tends to bifurcate, depending on the initial velocity. Initially fast-moving flows (>4–5 m s^{-1}) sustain near-uniform front velocities or gradually accelerate, and thus have large runout distances[4,87]. Flows that initially travel at slower speeds die out over much shorter distances[4,87] (**Fig. 7d**). It is not yet clear why some flows (but not others) reach these high initial speeds, but it could result from the initial remobilisation of large volumes of sediment, which produces thick, dense flows.

Three further key insights emerge from a comparison of the changes in flow speeds at different sites (**Fig. 7d**). First, previous theories predict that the sediment grain size and settling velocity should have a strong impact on the threshold flow speed needed for either ignition or autosuspension to occur[25]. However, similar threshold speeds (4–5 m s^{-1}) were observed in both sand-dominated (Monterey Canyon) and mud-dominated (Congo Canyon) settings[4,87]. The critical initial speed needed for ignition or autosuspension therefore appears to be independent of the settling velocity of the individual grains, perhaps because fast flows have dense near-bed layers in which grains interact with one another and do not settle individually. Second, although initial front speeds can effectively predict whether ignition or autosuspension will occur, they are a poor predictor of the runout distance, or depth and volume of erosion. For example, flows with speeds of 5–8 m s^{-1} in Congo Canyon ran out for >1,100 km, and eroded a huge sediment volume, equivalent to 19–35% of the annual flux from all rivers[4]. Whereas flows with similar initial speeds in Monterey Canyon ran out for >50 km and caused little net erosion of the seabed[35,52,87] (**Fig. 7d**). Last, although ignition does occur, it occurs gradually over long distances, and many flows tend towards a near-uniform front speed (**Fig. 7d**). Indeed, flows in the Congo Canyon exhibit combined elements of ignition (erosion of the seabed) and autosuspension[4] (near uniform flow front speeds).

These insights have led to the development of a travelling wave model (**Fig. 7e**), in which flows can be highly erosive (as for ignition) yet maintain near uniform speeds[4,87] (as for autosuspension). In this model, the turbidity current is driven by a dense, partially liquefied, near-bed frontal layer[4,87] (travelling wave). Erosion at the base of the dense layer, is balanced by sediment deposition or transfer into a trailing dilute sediment cloud, leading to near-uniform speeds (**Fig. 7e**). However, this model might not be applicable for turbidity currents in unconfined settings, such as basin plains, where very long (up to 2,000 km) runouts on low gradients (0.05 °) can occur without substantial seabed erosion[86,88]. In such settings, slow settling cohesive mud could provide the main driving force for the flow. Indeed, mud can form vast fluid-mud layers that only stop in bathymetric lows at the far end of deep-sea basins[86,89].

Observations in Monterey Canyon also suggest that seabed properties and processes of sediment erosion and entrainment from the seabed can impact turbidity current behaviour[87]. One of the 16 flows monitored during 2016–2018 accelerated within the mid-canyon, and was the only flow to occur in summer months[87]. Therefore, it is likely that this summer event either entrained a seasonally developed weak mud-layer, or triggered a local failure of the seabed, thereby causing an anomalous mid-canyon acceleration[87]. Time-lapse mapping of the Congo Canyon also shows that erosion of the seabed can be extremely patchy and localised on the canyon floor, despite flows speeds remaining relatively uniform[4,5]. Local areas of deep (20–30 m) erosion are associated with abrupt steps in the submarine channel **[G]** that resemble waterfalls, known as knickpoints. Indeed, observations of cable breaking events worldwide show that although adjacent cables break, some cables can survive fast flows, suggesting that uneven seabed erosion could be ubiquitous[4-6, 90]. It is not inevitable that a fast turbidity current will break a cable. It is possible that cables that break are located close to knickpoints, whereas cables that survive are located away from knickpoints[4,5]. This theory could be tested further by using time-lapse mapping. Understanding and predicting rates of seabed erosion remains challenging, and it is critical for flow modelling, as patterns of erosion or deposition could control flow behaviour[91].

[H1] How turbidity currents sculpt the seabed

It is important to understand how turbidity currents form submarine canyons and channels or how bedforms record flow states. Time lapse mapping of the seabed also provides new insights into how turbidity currents interact with the seabed[4, 17, 35, 38] and demonstrates important ways in which turbidity currents differ from terrestrial rivers[25]. For example, flows exist in one of two basic states: supercritical flow **[G]** , which is thin and fast, or subcritical flow, which is slow and thick. A critical Froude number (Fr) separates supercritical ($Fr > 1$) from subcritical ($Fr < 1$) flow, with this Froude number being proportional to flow speed and inversely proportional to the density contrast between the flow and the surrounding medium[92-95]. Subcritical flows occur in most terrestrial rivers and produce bedforms such as dunes and ripples that migrate down-slope. Turbidity currents are more prone to supercritical flow than rivers, owing to their lower density contrast with the surrounding seawater than that between river-water and air, and often faster speeds than rivers[92-95]. There is mounting evidence that supercritical turbidity currents are widespread on the seafloor[96]. For example, spectacular trains of up-slope migrating bedforms have been mapped on submarine canyon floors worldwide[35,38,39], on open continental slopes[96], and flanks of volcanoes[97]. Combined flow monitoring and time-lapse seabed mapping measurements suggest that these up-slope migrating bedforms are linked to instabilities in supercritical flows[38,50], known as cyclic steps. These instabilities can lead to repeated alternations of supercritical and subcritical flows separated by hydraulic jumps that lead to formation of trains of up-slope migrating bedforms[92-95].

Time-lapse mapping is also showing how up-slope migrating knickpoints that are 10–30 m high could dominate submarine channel-bend evolution[98,99] (**Supplementary Fig. 2**). Knickpoints can also occur in river channels. However, submarine knickpoints can move faster and travel further than those in rivers, migrating hundreds of meters each year, driven by overpassing turbidity currents[98, 99]. Knickpoints in rivers are formed by external processes such as fault-uplift, sea-level variation and changes in bedrock. Whereas submarine knickpoints are formed by internal processes such as cyclic steps or seabed loading and failure[98]. These seabed knickpoints excavate submarine channels and deposit sediment downstream[98] (**Supplementary Fig. 2**). Knickpoints also have a key role in determining how sediment, organic carbon and pollutants are shuffled in multiple stages to the deep-sea[100].

In meandering rivers, secondary (across-channel) flow at bends can sweep sediment towards the inner-bank to form point bars[24]. However, there has been vigorous debate on whether the secondary flow in turbidity currents occurs, with near-bed flow towards the inner-bank of a bend, as in rivers, or is reversed with near-bed flow towards the outer-bank[24,101,102]. Flow monitoring at a bend in the Congo Canyon suggests that two secondary flow cells occur, with near-bed flow sweeping sediment towards the outer bend[103]. But knickpoint migration might be more important than secondary flow patterns for bend evolution, at least in some settings[98,100] (**Supplementary Fig. 2**).

Turbidity currents were first proposed to explain the origin of huge underwater canyons that were discovered in the 1800s on ocean and lake floors[1,104,105]. Currently available time-lapse mapping only extends for ~25 years at most[92,106], but it is starting to help understand how these canyons form. For example, time-lapse mapping of the Kaikōura Canyon offshore Aotearoa New Zealand, before and after a major ($M_w = 7.8$) earthquake in 2016, shows that the earthquake caused widespread failure of the canyon-rim and other areas[17]. This failure produced a turbidity current that caused gravel waves to move down the canyon and eroded >1 km^3 of sediment, a volume that is 2–3 times larger than the amount of sediment that enters the ocean annually from Aotearoa New Zealand rivers. This flow swept seabed life from a canyon that previously had one of the highest benthic biomasses on Earth and carried ~7 Mt of particulate organic carbon to the deep-sea[17]. Additionally, time-lapse mapping of the Congo Canyon revealed that turbidity currents eroded ~2.6 km^3 of sediment in one year and flushed this sediment and associated organic carbon into the deep-sea[4]. These repeat surveys show that fresh organic carbon from river floods can be transported rapidly to the deep-sea by turbidity currents and explain how organic carbon can be efficiently buried by turbidity currents with long runout and high flow speeds[8].

Time-lapse measurements also show that canyon-flank collapse can produce landslide-dams with implications for the transfer of sediment and organic carbon through canyons to the deep-sea. For example, a ~0.09 km^3 canyon-flank landslide dammed the Congo Canyon, causing the temporary storage of a further ~0.4 km^3 of sediment with ~5 Mt of (mainly terrestrial) organic carbon[106]. The trapped sediment was up to 150 m thick and extended >26 km up the canyon from the landslide-dam, and this dammed sediment is currently being eroded and gradually released[106].

Meter-scale resolution seabed surveys using autonomous underwater vehicles (AUVs) that fly at just a few tens of meters above the seabed provide new insights into how submarine channel and submarine fan systems operate[35, 43, 52, 107-110]. Previous influential models of such systems assumed that channels bifurcated down-slope at their terminations, to form a distributary network, in the same way that many rivers bifurcate to create deltas[111]. However, AUV mapping of submarine channel mouth terminations shows that only a single main channel is active, although there could be scours and bedforms, as well as adjacent headless channels that are not connected to the main channel[109]. This channel mouth geomorphology is radically different to that seen in laboratory experiments[112], and its impact on flow processes remains poorly understood.

[H1] The formation of turbidity current deposits

Ancient turbidity current deposits (turbidites) form rock sequences in numerous locations worldwide, which can be kilometers thick, and accumulate over thousands to millions of years[111,113]. Geologists have used this rock record to propose models to describe how flows and deposits are linked; however, such models are difficult to test without direct flow observations[86]. Therefore, direct measurements from active flows are now being combined with analysis of seabed cores to directly demonstrate how deposits form a record of their parent flow. These direct measurements can produce insights, albeit only for processes that operate over short (days to a few years) time-scales, rather than longer term processes occurring over thousands of years.

For example, observations of deposits from seabed cores were combined with time-lapse mapping and direct flow measurements to show how trains of cyclic step bedforms created by supercritical flows[38] are recorded in deposits[50]. These measurements also showed that individual flow deposits primarily composed of massive sand are linked to dense near-bed layers. The up-slope migration of single bedforms initially produces backstepping stratal geometries; however, these features were then eroded by the migration of subsequent bedforms with complex and offset crests to leave complex nested scours[50,114].

Time lapse mapping has also been used to investigate the completeness of turbidite deposits, and how much of the initially deposited sediment is finally preserved in the rock record. For example, ~90 near-daily surveys spanning ~3 months (ref.[38]) were used to map patterns of erosion and deposition in the offshore Squamish Delta[115]. These surveys revealed that only 11% of the sediment deposits within channels was preserved, even on these very short (3 month) time scales[115]. Seabed cores and moored traps that capture sediment from within flows in Monterey Canyon were used alongside direct flow measurements to determine how flows were linked to seabed deposits[51,81,98]. This work showed that sand is restricted to a few meters above the canyon floor, and internal tides that occur between turbidity currents stir up fine-mud; therefore, fine-mud is poorly recorded in sand-dominated canyon floor cores[51]. Organic carbon can also be kept in suspension by internal tides, such that it is underrepresented in seabed cores[81].

A puzzling feature of individual ancient turbidite beds is that they have a distinctly bimodal distribution of thickness and internal deposit types[116]. Thicker (>40 cm) beds tend to contain intervals of massive and planar-laminated sand, whereas thin beds (<40 cm) tend to comprise only ripple cross-laminated sand and overlying mud[116]. Long distance mapping of individual turbidite deposits shows that these deposits can evolve from thick to thin beds, with a relatively sharp termination of massive and planar-laminated intervals comprising the thick bed[86,117]. Direct monitoring can now explain why turbidite deposits are bimodal [40]; fast flows contain a dense near-bed layer that deposits massive and planar-laminated sand, whereas slow flows are entirely dilute and produce thinner turbidite deposits with cross-bedding[40] (**Fig. 6c,e**).

[H1] Summary and future perspectives

Detailed direct monitoring of turbidity currents has led to major advances in understanding, including insights into the causes and frequency of turbidity currents, and their wider implications for global organic carbon fluxes and hazards to deep-sea cables and other infrastructure. Direct monitoring has also helped to understand what turbidity currents comprise, with faster (>1.5 m s^{-1}) flows having dense near-bed layers at their front, whereas slower moving flows are entirely dilute. New types of flow behaviour have been recognised, in which flows can both erode the seabed and maintain a near uniform speed. Time-lapse seafloor mapping and seabed coring have been combined with direct measurements within flows to document how turbidity currents mould the seafloor, and create submarine canyons, channels and bedforms, or form turbidite deposits.

There are now exciting opportunities to use direct monitoring data from turbidity currents to test computational or analytical flow models, design more realistic laboratory flume experiments, or understand deposits. These data indicate that models and flume experiments should simulate near-bed layers with high (10–30%) sediment concentrations for fast (>1.5 m s^{-1}) flows. A key challenge is to develop a robust theoretical framework for how such hyper-concentrated layers behave, in which turbulence is strongly damped, grain settling is hindered, yet deposition occurs incrementally rather than en-masse. This framework would be broadly comparable to that developed for even higher sediment concentration debris flows[118], in which en-masse deposition occurs.

This Review is also a rally call for widespread global monitoring of turbidity currents, over longer timescales, that is underpinned by a new generation of sensors that are deployed at substantially reduced cost and risk relative to present direct monitoring approaches. The current situation in the field of turbidity currents is broadly comparable to trying to understand how rivers work globally, using sporadic and incomplete monitoring from just ~10 sites, mainly smaller streams. Further research is needed in locations where the occurrence of turbidity currents would be more surprising, as shown by work in Whittard Canyon[69] (**Supplementary Fig. 1**), or other types of system such as those with hyperpycnal flows.

Present measurements are challenged by the fact that moored sensors are often broken by fast (>5 m s^{-1}) turbidity currents[4, 119]; therefore, other types of sensors are needed that can be placed outside of the active flow, and thus out of harm's way. Seismic signals[120] or acoustic noise[121] from turbidity currents could underpin a new generation of sensors that remotely sense turbidity currents from a safe distance. Indeed, an exciting development is that submarine landslides could also be remotely sensed using seismic signals, at low cost, over large ocean basins. Such signals indicate that 75 of the 85 landslides that occurred in a 7-year period in the Gulf of Mexico were triggered by remote and sometimes moderate earthquakes, which were hundreds or even thousands of kilometers away[122]. Low cost sensing systems are also needed that can relay data back through surface floats and satellites, rather than needing to be retrieved by expensive vessels[118]. Without these low cost systems data will remain limited to just a few sites.

Current direct monitoring techniques are good at measuring flow velocities. However, the most important parameter might be the sediment concentration (and thus excess density above that of surrounding seawater), as this density difference is what drives the flow[1], and determines the sediment mass-flux. Future monitoring should focus on how to measure the sediment concentration in turbidity currents, as well as how flows erode the seabed, as mass-exchange with the bed often dominates the overall flow behaviour[91]. Methods to constrain mass fluxes, together with a more global monitoring network could determine the global sediment and organic carbon fluxes carried by turbidity currents, and their fundamental controls, making it possible to explore how these fluxes compare to other major global sediment and carbon pumps on Earth (**Fig. 2a-c**).

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Author contributions

All authors researched data for the article. M.J.B.C., E.P., M.B., M.A.C., S.H., M.H., D.R.P., C.K.P., G.L. and P.J.T. contributed substantially to discussion of the content. P.J.T. wrote the article. M.J.B.C., E.P., M.B., M.A.C., S.H., M.H., D.R.P., C.K.P., R.G., G.L., R.S.J. and P.T. reviewed and/or edited the manuscript before submission.

Competing Interests

The authors have no competing interests.

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Key Points

- Previously, submarine turbidity currents were thought to be impractical to monitor in action, mainly owing to their ability to damage sensors in their path, but detailed monitoring is now possible, and it is revealing major new insights.
- Direct monitoring is identifying triggers for flows, such as very dilute river plumes, and consistently shows that turbidity currents occur much more frequently than predicted by past models such as, sequence stratigraphic models.
- Owing to turbidity currents, the global burial efficiency of terrestrial organic carbon (28–45%) in marine sediments is substantially higher than previous (10–30%) estimates, and even higher (>60–80%) during glacial low-stands.
- Fast (>1.5 m s^{-1}) turbidity currents are driven by a dense (10–30% concentration) near-bed layer at their front, which must be included in flow models, whereas slower flows are entirely dilute.

- This dense frontal layer sometimes erodes large sediment volumes (as for ignition), yet maintains a near-uniform speed (as for autosuspension), leading to a new (travelling wave) model for flow behaviour.
- Direct monitoring reveals how flows sculpt canyons and channels, such as through supercritical bedforms and internally generated fast-moving knickpoints, and how deposits record flow processes.

Glossary

Turbidity current: An underwater avalanche of sediment and water that is denser than the surrounding water, and thus moves down-slope along the ocean or lake floor.

Turbidite: Layer of sand and mud that has settled out from a turbidity current to form a deposit on the ocean or lake floor.

Ignition: Positive feedback leading to the acceleration of a turbidity current owing to seafloor erosion that causes the flow to become even faster and denser, leading to more erosion.

Autosuspension: A near-equilibrium state that occurs when the settling of sand and mud from a turbidity current is balanced by seafloor erosion, leading to near uniform flow velocity.

Dissipation: A negative feedback loop leading to the deceleration of a turbidity current, as the settling of sand and mud causes the flow to become less-dense and slower, causing further settling.

Acoustic Doppler current profiler: Sensor emitting a sound-pulse that is scattered from sand and mud particles within a turbidity current, which measures the speed of those particles at different heights above the seabed to produce a velocity profile.

Frontal cell: The frontal part of faster-moving ($>\sim 1.5 \text{ m s}^{-1}$) turbidity current that is faster than the rest of the flow, and contains a near-bed layer with high sediment concentrations.

Supercritical flow: Flows can exist in two basic states that are either thin-and-fast (‘supercritical’) flow or thick-and-slow (‘subcritical’) flow, which are separated by a hydraulic jump.

Submarine fan: A large-scale accumulation of sediment formed by turbidity currents that comprises a canyon, channel with levees (upraised flanks of a submarine channel that lie above the surrounding seafloor formed by the overspill of turbidity currents from the channel), and a lobe (a region that lies beyond the end of a submarine channel, where turbidity currents expand, often characterised by unusually rapid sediment deposition and scours).

Submarine canyon: A valley that is deeply incised into the seafloor through which turbidity currents flow, which is much deeper than a submarine channel.

Submarine channel: A channel that is less deeply incised into the seafloor than canyons through which turbidity currents flow, whose upraised flanks (called levees) can lie above the surrounding seabed.

Remineralisation: The process by which organic carbon is turned into CO_2.

Varve: A thin layer of fine sediment that represents the deposit of a single year within a lake.

Figures

Figure 1. Comparison between turbidity currents and other major global sediment transfer processes. a | The distances that flows travel and their velocities. **b** | Mass of sediment carried by individual events (red), and as annual sediment mass fluxes (black), with the grey bars showing the uncertainty. The sediment mass carried by the Grand Banks turbidity current in 1929 (ref.[3]) and Congo Canyon turbidity currents in 2020 (ref.[4]) are shown by the blue and green dotted lines respectively. Supplementary Table 1 provides further information and lists the source literature used for the distances, speeds, masses or annual mass fluxes. These data show that turbidity currents are one of the most important sediment transfer processes ('pumps') on Earth.

Figure 2. Turbidity currents have a globally important role in organic carbon burial. a | Global sediment mass fluxes (see Figure 1 and Supplementary Table 1 for original data sources). **b** | Global organic carbon mass fluxes. A future challenge will be to quantify global sediment and organic carbon fluxes in turbidity currents[14]. An estimated 62–90 Mt yr^{-1} of terrestrial organic carbon is buried in marine sediments by turbidity currents[14]. **c** | Pathways for global organic carbon cycling. The burial of organic carbon by turbidity currents affects the atmospheric partial pressure of CO_2 (pCO_2) and thus climate over long term (>1 ka) time scales. The black and blue arrows indicate the terrestrial organic carbon pathways and marine organic carbon pathways, respectively. Processes that exchange carbon with the atmosphere on short term (<~100 yr) timescales are shown by the purple arrows. **d |** The burial of organic carbon by turbidity currents can be highly efficient, such as within the huge Bengal Submarine Fan[8]. Organic carbon types and amounts in river samples (white stars) resemble those in deep-sea cores[8] (red stars). Part d is from ref.[123], Springer Nature Limited, and modified using data from GEBCO_2021 Grid, www.gebco.net.

Figure 3. Direct monitoring of turbidity currents. a | Map of the 12 locations (red stars) worldwide where turbidity currents have currently been monitored in detail[27-54,61,69, 124-125] and other key locations (yellow circles) mentioned in this Review. **b**,**c**,**d** | Flow monitoring has moved from **(b)** small systems in shallow water such as the Squamish Delta[38-39,50,59,60,115] where logistics are easier, to **(c)** larger systems in moderate depths such as in Monterey Canyon[34,35,51-52,61,87], and **(d)** finally to very large systems in deep-water such as the Congo

Fan, where turbidity currents broke the West Africa Cable System (WACS) and South Atlantic (SAT-3) telecommunication cables (dotted lines) in 2020 and 2021 (ref.[4,36,37]). **e |** An acoustic Doppler current profiler (ADCP) mooring on the deck of a research vessel before it was deployed in Congo Canyon. Such moorings are used to monitor the flow, with the ADCP housed in a buoyant float connected to a heavy anchor (weighing approximately 1 tonne) through a wire or chain, and recovered by remotely triggering an acoustic release[119]. **f** | A heavy frame weighing 800 kg that slid for ~7 km down Monterey Canyon at speeds of up to 4.4 m s^{-1} (ref.[35,52]). It moved at a similar speed to much smaller and lower density objects, suggesting that these objects were rafted when entombed in a dense near-bed layer of sediment.

Figure 4. Insights into the causes of turbidity currents. a | Four main causes of turbidity currents[55,56] are slope failures (landslides); plunging of hyperpycnal river plumes that are denser than seawater owing to the high sediment concentrations[57]; sediment settling from surface river plumes[39,47-48,58]; and oceanographic processes such as storm waves, tides and internal waves that can supply sediment to canyon heads and trigger flows (including through landslides). **b |** There can be substantial delays between periods of rapid sediment accumulation in canyon heads, and the final triggering of turbidity currents by subtle external triggers[4,60-61]. **c,d |** River floods and tides combine to generate turbidity currents at many sites worldwide, including four extremely powerful turbidity currents (red stars) that flushed the Congo Canyon in 2020–2022 (ref.[4,5]). These canyon-flushing turbidity currents are associated with major floods along the Congo River, but occurred several weeks to months after the flood peaks, often at spring tides[4,5]. The tidal coefficient is the size of the tide in relation to its mean. Parts c and d are adapted from ref.[4], Springer Nature Limited.

Figure 5. Submarine fans and frequency of turbidity current activity. a | Summary of the main elements of a submarine fan. **b |** Sedimentation rates in different parts of the Congo Submarine Fan[126]. **c |** At glacial low-stands in sea-level, most river mouths are directly connected to the submarine canyon-head[67,68], meaning that the turbidity currents are highly active[66,70]. There are a small number of modern canyon-heads that are highly active because they still connect directly to river mouths, such as the Congo Canyon[4] or Gaoping Canyon [9,41,42]. **d |** Previous models (such as sequence stratigraphic models) proposed that submarine canyons are dormant during high-stands in sea-level[66], because river mouths are separated from most canyon heads. **e |** There is an emerging view that turbidity current systems are

surprisingly active during the present day high-stand in sea-level[70] because sediment can also be transferred efficiently across the shelf by waves or tide action to the canyon head[73,74], or through the progradation of large clinoforms[72].

Figure 6. Insights into the internal structure of turbidity currents. a | Velocity time-series of a turbidity current in Congo Canyon measured with an Acoustic Doppler current profiler (ADCP) mooring. **b |** Summary of the velocity structure of turbidity currents in Congo Canyon, comprising a near-bed frontal zone (frontal cell) that is faster and denser than the rest of the flow (inset), and runs away from a trailing body and tail, causing the flow to stretch[36]. **c-e |**. Time-series of velocity and layer-average sediment volume concentration derived using the Chezy equation of the three types of turbidity currents observed in Bute Inlet. Type 1 flows (**c**) have a frontal cell with a fast (>1.7 m s^{-1}) and dense near-bed layer, as in Congo Canyon flows, which drives the event and dominates sediment flux[40]. Type 2 flows (**d**) have intermediate speeds and sediment concentration. Type 3 flows (**e**) are slow, entirely dilute, and lack a dense and fast frontal layer. A single turbidity current can evolve from Type 1 to Types 2 and 3 as it decelerates[40]. The right inset shows the inferred types of turbidite deposit likely formed by different types of flow, with Bouma sequence intervals (T_A to T_E) marked[40]. Parts a and b are adapted from ref.[36], CC BY 4.0. Parts c,d and e are adapted from ref.[40], CC BY 4.0.

Figure 7. A new view of how turbidity currents behave. a,b,c | Past models inferred that flows either **a** | deposited sediment and dissipated; **b |** eroded, became denser and faster, and accelerated (ignited); or **c |** balanced erosion and deposition to create a near-equilibrium uniform velocity (autosuspending) state[25]. Red arrows denote flow speed; black arrows indicate sediment exchange with the bed. **d |** Summary of the changes in flow front speeds observed with direct field measurements, illustrating three key points. (1) Flow behaviour diverges depending on whether the initial speed exceeds the threshold speed of 4–5 m s^{-1} (ref.[4,87]). Above this threshold, flows accelerate or sustain their speed, and travel for longer distances. Flows that are initially slower than this threshold decelerate and dissipate. This threshold speed is independent of the dominant sediment grain size. (2) After initial ignition–autosuspension flows with similar front speeds can runout for highly variable distances, and erode to very different degrees. (3) Small changes in flow front speeds occur over long distances; sometimes despite flows eroding large sediment volumes. **e |** New ‘travelling

wave' model in which flows can both erode the seabed (as in ignition) and sustain near uniform speeds for long distances[4,87] (as in autosuspension). The flow contains a dense frontal layer in which seabed erosion is balanced by sediment shed back into a dilute trailing body. Part d is adapted from ref.[4], Springer Nature Limited.

TOC blurb:

Seafloor turbidity currents form Earth's largest sediment accumulations, deepest canyons and longest channels, but their destructive nature makes them notoriously difficult to measure in action. This Review explores how insights from detailed direct measurements have advanced understanding of turbidity currents.