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1 Detailed monitoring reveals the nature of submarine turbidity currents

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20

21 Abstract

22

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

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

39

40 **[H1] Introduction**

41

42 **Turbidity currents [G]** are mixtures of sediment and water that travel downslope because they
43 are denser than the surrounding water¹. These currents can have prodigious scale and power<sup>2-
44 7</sup> (**Fig. 1; Supplementary Table 1**). For example, a turbidity current in 1929 broke all of the
45 telecommunication cables across the NW Atlantic and had a sediment volume of
46 approximately 200 km³ (ref.^{2,3}), which is ~30 times larger than the global annual sediment
47 flux from rivers, and exceeds that of the largest subaerial landslide (~50 km³) in the last
48 350,000 years (**Fig 1b; Supplementary Table 1**). These cable breaks showed that the 1929
49 flow travelled at speeds of up to 19 m s⁻¹ and ran out for over 800 km (ref.^{2,3}) (**Fig. 1a**).
50 Additionally, in 2020, turbidity currents that initiated at the mouth of the Congo River
51 travelled >1,100 km through the Congo Submarine Canyon offshore West Africa⁴ (**Fig. 1a**),
52 accelerating from 5 to 8 m s⁻¹ and eroding ~2.65 km³ of sediment (**Fig. 1b**). These 2020 flows
53 broke both seabed telecommunication cables to West Africa, causing the internet to slow
54 from Nigeria to South Africa, just when capacity was most needed during Covid-19 related
55 lockdowns^{4,5}.

56

57 Turbidity currents are important for many reasons. As shown by the 1929 NW Atlantic and
58 2020 Congo Canyon flows, turbidity currents commonly break networks of seabed
59 telecommunication cables²⁻⁷ that now carry over 99% of global intercontinental data traffic,
60 as they have much larger bandwidth than satellites⁷. These cables form the backbone of the
61 internet, and are critical for many aspects of daily life, from intercontinental phone traffic to
62 financial markets and cloud data storage⁷. Turbidity currents also have an important role in
63 the transfer and burial of fresh organic carbon in marine sediments, which remove CO₂ from
64 the atmosphere, regulating climate over geological time scales⁸⁻¹⁰ (**Fig. 2**). It was once
65 thought that terrestrial organic carbon supplied to the oceans was mainly oxidized on
66 continental shelves¹¹⁻¹³, and turbidity currents were omitted from analyses of global carbon
67 cycles¹¹⁻¹³. However, the burial of terrestrial organic carbon through turbidity currents can be
68 highly efficient^{8,9}, and global estimates of organic carbon burial in marine sediments might

69 thus need to be revisited¹⁴ (**Fig. 2b**). Organic carbon is also the basis for all non-
70 chemosynthetic marine food webs, and turbidity currents could thus have a key role in
71 determining how seabed ecosystems function^{15,16}. For example, rapid and sustained
72 deposition of organic-carbon-rich sediment by turbidity currents can favour chemosynthetic
73 communities¹⁶, whilst extremely powerful flows can sometimes scour life from the
74 seafloor^{5,17}.

75
76 Turbidity currents and their carbon transport are linked to human activities, as they can be
77 generated by seabed trawling¹⁸. These flows also transfer microplastics and other pollutants
78 generated by human activities into the deep-sea¹⁹. Additionally, turbidity current deposits
79 (called **turbidites [G]**) can provide a record of Earth history, including long-term and
80 therefore valuable records of other important geohazards such as major earthquakes²⁰⁻²², or
81 river-floods⁴; although it can be very challenging to infer the triggering mechanism for an
82 ancient turbidite with confidence. Thick and extensive turbidite deposits in the rock record
83 also host major oil and gas reserves in many locations worldwide²³. Major advances in
84 understanding have previously been made using analyses of rock outcrops, seabed cores, and
85 turbidity currents within laboratory experiments or numerical models^{1,24-26}.

86
87 Perhaps the most remarkable aspect of submarine turbidity currents is how few direct
88 measurements of these flows were previously available²⁷⁻³¹, ensuring that they were poorly
89 understood³². Indeed, it was once thought to be impractical³³ to measure turbidity currents
90 directly in the oceans, owing to their location, infrequent occurrence, and ability to badly
91 damage (or entirely remove) sensors in their path. However, since the mid 2010s, a series of
92 ambitious projects have used new sensors and methods to provide the first detailed
93 measurements within submarine turbidity currents (**Fig. 3**). For example, these projects
94 consistently use **acoustic Doppler current profilers [G]** (ADCPs) mounted on moorings (**Fig.**
95 **3e**) to measure flow velocity profiles at frequencies of seconds to minutes, including at
96 multiple places along the flow pathway³⁴⁻⁵³. ADCPs emit a sound-pulse that is scattered from
97 sand and mud particles within a turbidity current and measure the speed of those particles at
98 different heights above the seabed to produce a velocity profile. Projects were initially
99 conducted in shallow (< 500 m) water^{38,39}, where logistics are easier and costs lower, before
100 moving into deeper (up to 2 km) water³⁵⁻³⁷, and then finally capturing extremely large events
101 that reach depths of 4–5 km (ref.⁴) (**Fig. 3b-d**). Direct flow monitoring has been combined
102 with detailed time-lapse mapping of the seabed^{35,38,39,54}, tracking of heavy objects^{35,53} (**Fig.**

103 **3f)**, sediment traps inside the flow^{41-42,51}, and coring of seabed deposits^{50,51} to advance
104 understanding of how turbidity currents work. These projects have not been without
105 challenges and risks, such as needing to recover broken moorings drifting across the ocean
106 surface near the Congo Canyon before their locator beacons stopped transmitting, all during a
107 Covid-19 related lockdown^{4,5}, finding and recovering severed and buried cabled
108 infrastructure⁴⁸, or when turbidity currents occurred only on the last days of field
109 campaigns⁵⁰.

110

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

120

121 **[H1] Causes of turbidity currents**

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

133

134 It was previously thought that surface river plumes could only generate turbidity currents
135 when sediment concentrations in rivers exceeded 1 kg m^{-3} . However, direct measurements of

136 sediment concentrations in rivers and monitoring of turbidity currents at Squamish Delta
137 (Canada) showed that surface river plumes with sediment concentrations as low as 0.07 kg m^{-3}
138 ³ can generate turbidity currents³⁹, sometimes even more frequently than landslide-triggered
139 turbidity currents⁵⁹. Therefore, a much larger fraction of global river mouths have the
140 potential to generate turbidity currents than was once thought³⁹. The exact mechanism by
141 which turbidity currents originate from below such dilute surface plumes is still uncertain, but
142 it could be linked to the generation of mobile fluid-mud-like layers on the seabed^{39,47,48}, or
143 sediment trapping through estuarine circulation, or both³⁹.

144

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

152

153 However, there might be a significant time delay between a river flood peak, and the eventual
154 final trigger of a turbidity current. For example, the very large turbidity currents in the Congo
155 Canyon occurred several weeks to months after the Congo River's flood peak, typically at
156 spring tides⁴ (**Fig. 4c**). A similar pattern is seen elsewhere, albeit with shorter delays. A
157 turbidity current occurred 2–3 days after a huge flood along the Gaoping River in Taiwan⁶,
158 although in this case the final trigger was not a spring tide, whereas landslide-triggered
159 turbidity currents occurred hours after the flood peak at the Squamish Delta⁶⁰. Therefore, it
160 appears that **submarine canyon [G]** heads store sediment (acting as a capacitor), which is later
161 discharged, often owing to a minor external perturbation, such as spring tides and other
162 mechanisms^{4,60,61} (**Fig. 4d**). Such time delays complicate the relationship between the timing
163 of major external events (such as, floods and earthquakes) and turbidity currents. Indeed, in a
164 few cases, direct measurements show that turbidity currents can be triggered without any
165 obvious synchronous external trigger. For example, a turbidity current that moved at $4\text{--}7 \text{ m s}^{-1}$
166 ¹ and ran out for 50 km in Monterey Canyon occurred on a day without a storm, river flood or
167 earthquake⁶¹.

168

169 It is important to understand the triggers of canyon-flushing turbidity currents because it has
170 been proposed that deep-sea turbidites can record major earthquakes in some settings. If
171 reliable, turbidite paleo-seismology would be valuable, as these marine records go back
172 further in time than almost all land-based records²⁰⁻²². However, care is needed as there are
173 potential pitfalls. Earthquake triggered turbidites need to be reliably distinguished from
174 turbidites triggered in other ways, and it is important to test whether all (or only some) major
175 earthquakes trigger distinctive turbidity currents^{21,22}. It has been proposed that earthquakes
176 are the only events to produce synchronous turbidites (layers of sand and mud) over very
177 extensive (>100 km) areas²⁰. However, it is difficult to correlate individual turbidite layers
178 over such distances, especially for ancient layers if the uncertainties in radiocarbon dates are
179 similar to the earthquake recurrence intervals^{20,22}. Turbidite layers could also be emplaced
180 due to tropical cyclones that affect areas comparable to those of major earthquakes²².
181 Turbidites with multiple fining-upward cycles of grain size have been linked to peaks in
182 ground motion during earthquakes²⁰, but turbidity currents with multiple pulses can also be
183 generated by river floods^{36,37,46}. Repeated shaking owing to earthquakes could also potentially
184 cause sediment to consolidate and become stronger in some locations⁶². Despite these
185 challenges, substantial advances have been made in assessing the reliability of the
186 identification of earthquake triggered turbidites, and understanding which sites are better
187 suited for turbidite paleoseismology. For example, there was a consistent spatial relationship
188 between earthquake induced ground motion during the 2016 Kaikōura earthquake and
189 coseismic turbidites²¹. Additionally, the moment magnitude (M_w) 9 Tohoku-Oki earthquake
190 offshore Japan in 2011 remobilised a layer of surface sediment that was just a few
191 centimeters thick over a large area where ground motion was strongest⁶³. Turbidites that are
192 precisely dated using **varves [G]** in lakes can be correlated with confidence and provide
193 compelling evidence for earthquake triggering⁶⁴.

194
195 Direct monitoring can also test how turbidity currents can record major river floods^{46,58}. For
196 example, a single flood from the Congo River produced a cluster of multiple offshore
197 turbidity currents in the following years⁴ (**Fig. 4c**). Direct monitoring of the Var system in the
198 Mediterranean revealed that (non-earthquake) landslides and floods produced turbidity
199 currents with multiple pulses; therefore, multi-pulsed deposits are not a unique criterion for
200 identifying earthquake or flood triggering⁴⁶. Finally, turbidites can also provide important
201 insights into how volcanic islands collapse⁶⁵, and whether this collapse occurs in one or
202 multiple stages, which is critically important for assessing the tsunami magnitude.

203

204 **[H1] Flow frequency**

205 This section outlines insights into the frequency of turbidity currents, and some of their wider
206 implications, such as for the transfer and burial of organic carbon or seabed life. Direct
207 monitoring of turbidity currents has consistently found that turbidity currents are more
208 frequent than previously predicted (**Fig. 5; Supplementary Fig. 1**), such as by sequence
209 stratigraphic models⁶⁶ (**Fig. 5c,d**). These sequence stratigraphic models infer that most
210 modern turbidity current systems are inactive, with activity being mainly restricted to periods
211 of falling or low global sea-level⁶⁶ (**Fig. 5c**). This reduced turbidity current activity is because
212 post-glacial sea-level rise has flooded continental shelves, ensuring that almost all modern-
213 day submarine canyon-heads are detached from river mouths (**Fig. 5**), with only ~180 of
214 ~9,500 submarine canyons currently extending to within 6 km of shore^{67,68}.

215

216 However, direct monitoring now shows that modern-day turbidity current systems can be
217 highly active in a range of settings (**Supplementary Fig. 1**). For example, over 100 turbidity
218 currents occurred on Squamish Pro-delta in Canada in ~3 months (ref.^{38,39,59,60}), and turbidity
219 currents in the upper Congo Canyon can last for over a week and are active ~30% of the
220 time^{36,37}. Turbidity currents have even been observed in canyons fed by rocky shorelines that
221 lack obvious sediment sources⁴³. Powerful canyon-flushing turbidity currents might also be
222 more frequent than once thought, as they can be linked to river floods with recurrence
223 intervals of a few decades⁴ (**Fig. 4c**), as well as major earthquakes with longer recurrence
224 intervals¹⁷. Frequent and powerful flows have also been measured outside of submarine
225 canyons and channels. For example, dozens of flows occurred on the open-slope of the Fraser
226 Pro-delta, some with velocities of $>6 \text{ m s}^{-1}$ (ref.^{47,48}). Most surprisingly, 4–6 powerful (5–
227 8 m s^{-1}) flows occurred in Whittard Canyon during 14 months from June 2019 to August
228 2020, despite this canyon being $>300 \text{ km}$ from the nearest shoreline⁶⁹ (**Supplementary Fig.**
229 **1a-c**). Indeed, turbidity currents are as frequent in Whittard Canyon in the N.E. Atlantic as
230 Monterey Canyon in California, whose head is located tens of meters from the shoreline^{15,35}.
231 There are several thousand other shoreline-detached canyons similar to Whittard Canyon^{67,68},
232 and these findings raise the question of what their flow activity might be⁶⁹.

233

234 These findings from direct monitoring are consistent with those from previous approaches
235 based on dated turbidites on sediment cores that challenged the prevailing models of dormant

236 turbidity current systems during sea-level high-stands⁷⁰ (**Fig. 5c,d**). Other lines of evidence
237 than direct monitoring also suggested that turbidity currents could efficiently transfer
238 sediment to the deep-sea, even when submarine canyon heads are not located within a few
239 kilometers of river mouths (**Fig. 5e**). Prograding wedges of sediment (clinoforms) offshore
240 from major rivers can reach canyon heads (**Fig. 5e**). For example, the Ganges-Brahmaputra
241 River, which supplies ~16% of all riverine sediment to the ocean⁷¹, is highly active despite
242 having a submarine canyon-head 130 km from the river mouth, owing to the presence of a
243 clinoform on the shelf⁷². Oceanographic processes are likely to have a key role in producing
244 these highly active turbidity current systems located far from river mouths. For example,
245 waves and tides can resuspend sediment and efficiently transport it across continental shelves
246 to submarine canyons⁷³, such as, in the continental shelf offshore from the Eel River where
247 70–80% of sediment was lost over the shelf edge⁷⁴.

248

249 **[H1] Implications for carbon transport**

250 The present turbidity current pump might be much more active than previously thought (**Fig.**
251 **2**), which could have important implications for the transfer and burial of organic carbon in
252 the deep-sea^{8,14}, which affects atmospheric CO₂ levels and thus climate over long
253 (>1,000 year) time scales^{8,10,13,14}. Previous analyses of global carbon burial in the oceans have
254 largely neglected the role of turbidity currents, assuming that terrestrial organic carbon
255 supplied by rivers is buried almost exclusively within deltas or continental shelves^{11,12}.
256 Additionally, these analyses assumed that there was **remineralization [G]** of most terrestrial
257 organic carbon on the continental shelves, leading to the release of CO₂, as occurs offshore
258 from the Amazon River^{11,12,75}, such that the global burial efficiency of terrestrial organic
259 carbon in marine sediments was low¹¹⁻¹³ (10–44%).

260

261 However, comparisons of organic carbon types in major rivers and deep-sea **submarine fan**
262 **[G]** turbidites suggest that terrestrial organic carbon burial by turbidity currents can be highly
263 efficient (>60–100%) in settings ranging from the exceptionally large Bengal Fan⁸ (**Fig. 2d**),
264 to fjords⁷⁶, and systems fed by small mountainous rivers in Oceania⁹. These findings led to
265 revised global estimates of the mass-flux (~62–90 MtC yr⁻¹) and efficiency (31–45%) of
266 terrestrial organic carbon burial in marine sediments¹⁴. Photosynthesis in the ocean surface
267 produces organic carbon at a very fast rate⁷⁷ (50,000 MtC yr⁻¹), but only 90–130 MtC yr⁻¹ of
268 that marine carbon is buried at the seabed^{10-14,77} (**Fig. 2b**). Thus, the burial flux of terrestrial

269 organic carbon by turbidity currents is close to that caused by the settling of marine carbon
270 from the ocean surface¹⁴. However, only the production of marine carbon through
271 photosynthesis in the ocean surface will affect the atmospheric partial pressure of CO₂
272 (pCO₂) and thus the climate on short (<100 yr) time scales⁷⁸ (**Fig. 2c**).

273

274 During glacial low-stands almost all rivers would be directly connected to a submarine
275 canyon^{67,68}, increasing the efficiency of terrestrial organic carbon burial in the oceans from
276 ~31–45% to >60–80% (ref.¹⁴). Therefore, it is possible that the rate of terrestrial organic
277 carbon burial by turbidity currents varies systematically and substantially throughout glacial–
278 interglacial cycles⁷⁹. It is often inferred that during glacial periods increases in surface ocean
279 productivity further reduced atmospheric pCO₂ levels⁷⁸. However, increases in the efficiency
280 of terrestrial organic carbon burial by turbidity currents could also act as a positive feedback
281 to reduce atmospheric pCO₂ levels during glacial low-stands, albeit over much longer
282 (>1,000 years) timescales than changes in surface ocean productivity⁷⁹. Thus, the magnitude
283 of the difference in the turbidity current organic carbon burial flux between glacial and inter-
284 glacial periods (~30–95 Mt yr⁻¹) could be comparable with changes in the rate of global
285 organic carbon burial that are proposed to drive other longer-term climate fluctuations¹⁴. For
286 example, a comparable reduction in the global organic carbon burial flux (~90 Mt yr⁻¹) was
287 an important positive feedback for driving global warming during the Neogene⁸⁰.

288

289 A more active turbidity current carbon pump could also have important implications for
290 seabed life, as organic carbon underpins most marine food webs^{81,82}. Additionally, turbidity
291 currents can physically disturb ecosystems by scouring the seabed, sometimes to depths of
292 tens of meters, or by depositing thick sediment layers that smother ecosystems¹⁷. The rapid
293 accumulation of sediment rich in organic matter can also lead to the formation of
294 chemotrophic ecosystems resembling those that are present around black smokers⁸². Thus,
295 the impacts of turbidity currents on marine life warrant further analysis.

296

297 Monitoring projects have also revealed that human activities might trigger turbidity currents,
298 and thus impact wide areas of the seafloor. For example, bottom trawling can both smooth
299 (plough) the seabed, and initiate turbidity currents that travel down canyons¹⁸. This canyon-
300 monitoring work built upon previous, remarkably determined, efforts to record how cold and
301 dense water masses formed on continental shelves can cascade down submarine canyons⁸³. It
302 took almost a decade of research cruises to record these strong dense water cascades in

303 action, but it showed how direct measurements can lead to major advances⁸³. Turbidity
304 currents can also disperse microplastics and other pollutants¹⁹, or ventilate the deep ocean
305 with warm, oxygenated water⁸⁴.

306

307 **[H1] The internal composition of turbidity currents**

308

309 This section uses direct monitoring observations to understand the internal structure and
310 composition of turbidity currents. There has long been controversy over what turbidity
311 currents comprise^{1,26,85-86}. This debate centres on whether turbidity currents are entirely dilute
312 and fully turbulent sediment suspensions, as for most rivers, or driven by dense near-bed
313 layers that resemble debris flows^{1,26,85-86}. This debate is not just a minor detail; it is critical
314 because the physics of dense or dilute sediment flows are very different, and it is important to
315 know which type of flow to model in the laboratory or numerically⁸⁶. Geologists tried to
316 answer this question by examining turbidite deposits; however, the findings are often unclear,
317 especially when the deposits comprise massive or planar laminated sand⁸⁶.

318

319 Detailed measurements within turbidity currents, such as from ADCPs, have a key role in
320 understanding their internal nature (**Fig. 6**). Such measurements reveal that the velocity
321 structure of turbidity currents can differ substantially from laboratory experiments, where a
322 fast-moving body feeds a slow-moving head³³ (**Fig. 6b**). Measurements from the Congo
323 Canyon show that turbidity currents instead comprise a fast-moving frontal zone (**frontal cell**
324 **[G]**) that outruns a much slower-moving body, leading to flow stretching^{36,37} (**Fig. 6a,b**).
325 Such stretching could explain the surprising week-long duration of flows in the Congo
326 Canyon flows (**Fig. 6a**). Elsewhere, sand-dominated turbidity currents also display a short-
327 lived (<30 min) frontal cell where velocities are fastest (**Fig. 6c**), but these flows only lasted
328 for minutes to hours^{34,35,41,45,46,50,53} (**Fig. 6c; Supplementary Fig. 1d**). These flows lacked the
329 sustained week-long body seen in Congo Canyon flows, presumably because Congo Canyon
330 flows contain more mud, which settles slower than sand^{36,37}.

331

332 There is also mounting evidence that fast ($>1.5 \text{ m s}^{-1}$) turbidity currents contain dense near-
333 bed layers at their front, which drive the flow^{35,38,40} (**Fig. 6**). Multibeam echosounders
334 observed dense near-bed layers in fast-moving ($>1.5 \text{ m s}^{-1}$) flows at Squamish Delta³⁸;
335 however, the exact sediment concentration of these layers is unknown. Transit (flow front)

336 velocities derived from flow arrival times at ADCP-moorings in Monterey Canyon were
337 quicker than the maximum velocities measured by ADCPs inside the flow³⁵. This finding was
338 initially puzzling, as the flow front must push through surrounding seawater that retards its
339 progress. However, ADCPs typically do not measure the flow within a few meters of the bed,
340 suggesting that there could be a thin and fast layer near the bed³⁵. Even more surprisingly,
341 very heavy (up to 800 kg), dense (up to 6 g cm⁻³) and irregularly shaped objects (**Fig. 3f**)
342 were carried several kilometres down Monterey Canyon at speeds of up to 4 m s⁻¹,
343 comparable to the maximum flow speeds^{35, 52}. These objects had different masses, densities
344 and shapes, yet sometimes moved synchronously together^{35, 52}. In this case it appears that the
345 dense near-bed layers entombed and rafted the heavy objects. This conclusion is supported by
346 measurements from a conductivity probe that recorded high sediment volume concentrations
347 of >11% close to the bed⁴⁹.

348

349 The Chezy equation can be used to predict vertically-averaged sediment concentrations using
350 independently measured flow velocities and thicknesses, and a friction coefficient (**Fig. 6c-e**).
351 This equation was applied to turbidity currents in Bute Inlet (Canada), showing that fast
352 (>1.5 m s⁻¹) flows are relatively dense (with volume concentrations of >10% and up to 38%
353 sediment volume; **Fig. 6c**), whereas slower moving flows are entirely dilute⁴⁰ (**Fig. 6e**). The
354 dense parts of the flows carry most of the sediment and drive the overall event⁴⁰, and they are
355 likely to be characterised by strongly damped turbulence and hindered settling, as well as
356 grain-to-grain interactions. There is additional evidence to support the view that slow moving
357 flows are entirely dilute (**Fig. 6e**). For example, acoustic backscatter measurements from
358 ADCPs can be used to derive sediment concentrations, after making some assumptions about
359 grain sizes^{36, 37}. This method concludes that in the Congo Canyon the overlying sediment
360 cloud and trailing body (**Fig. 6a**) typically has sediment concentrations of just 0.1 to 0.001%
361 by volume³⁷.

362

363 Field evidence also supports the idea that flows could evolve from having a dense near-bed
364 layer to become entirely dilute and fully turbulent as they decelerate^{35, 40}. For example, dense
365 near-bed layers were not observed by multibeam sonars in slow flows at Squamish Delta³⁸,
366 and objects were not carried for such long distances at distal sites in Monterey Canyon³⁵.
367 Additionally, analyses using the Chezy-equation demonstrated that flows can evolve from
368 having a dense frontal layer to being entirely dilute as they decelerate⁴⁰ (**Fig. 6c-e**).

369

370 [H1] Behaviour of turbidity currents

371

372 This section seeks to understand the spatial and temporal evolution of turbidity currents, and
373 thus how they behave. Submarine turbidity currents have some similarities to terrestrial river
374 systems, such as the way they can both produce meandering channels; however, their
375 behaviour differs in some fundamental regards²⁴. Unlike rivers, turbidity currents are driven
376 by the weight of the sediment that they carry, and density differences with the surrounding
377 seawater. There are three basic hypotheses that describe the behaviour of turbidity currents
378 (**Fig. 7**). First, the deposition of sediment can reduce the density and thus velocity of the flow,
379 leading to further sediment settling, and consequently flow **dissipation [G]** (**Fig. 7a**). Second,
380 turbidity currents that erode the seabed can increase in density and speed, as more sediment is
381 incorporated into the flow, causing even more erosion and acceleration, producing a positive
382 feedback effect known as **ignition [G]**²⁵ (**Fig. 7b**). Last, the rate of erosion and deposition of
383 sediment could be balanced, such that turbidity currents maintain a uniform velocity and near
384 equilibrium state termed **autosuspension [G]**^{4, 25} (**Fig. 7c**).

385

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

395

396 Three further key insights emerge from a comparison of the changes in flow speeds at
397 different sites (**Fig. 7d**). First, previous theories predict that the sediment grain size and
398 settling velocity should have a strong impact on the threshold flow speed needed for either
399 ignition or autosuspension to occur²⁵. However, similar threshold speeds ($4\text{--}5\text{ m s}^{-1}$) were
400 observed in both sand-dominated (Monterey Canyon) and mud-dominated (Congo Canyon)
401 settings^{4,87}. The critical initial speed needed for ignition or autosuspension therefore appears
402 to be independent of the settling velocity of the individual grains, perhaps because fast flows

403 have dense near-bed layers in which grains interact with one another and do not settle
404 individually. Second, although initial front speeds can effectively predict whether ignition or
405 autosuspension will occur, they are a poor predictor of the runout distance, or depth and
406 volume of erosion. For example, flows with speeds of 5–8 m s⁻¹ in Congo Canyon ran out for
407 >1,100 km, and eroded a huge sediment volume, equivalent to 19–35% of the annual flux
408 from all rivers⁴. Whereas flows with similar initial speeds in Monterey Canyon ran out for
409 >50 km and caused little net erosion of the seabed^{35,52,87} (**Fig. 7d**). Last, although ignition
410 does occur, it occurs gradually over long distances, and many flows tend towards a near-
411 uniform front speed (**Fig. 7d**). Indeed, flows in the Congo Canyon exhibit combined elements
412 of ignition (erosion of the seabed) and autosuspension⁴ (near uniform flow front speeds).

413

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

425

426 Observations in Monterey Canyon also suggest that seabed properties and processes of
427 sediment erosion and entrainment from the seabed can impact turbidity current behaviour⁸⁷.
428 One of the 16 flows monitored during 2016–2018 accelerated within the mid-canyon, and
429 was the only flow to occur in summer months⁸⁷. Therefore, it is likely that this summer event
430 either entrained a seasonally developed weak mud-layer, or triggered a local failure of the
431 seabed, thereby causing an anomalous mid-canyon acceleration⁸⁷. Time-lapse mapping of the
432 Congo Canyon also shows that erosion of the seabed can be extremely patchy and localised
433 on the canyon floor, despite flows speeds remaining relatively uniform^{4,5}. Local areas of deep
434 (20–30 m) erosion are associated with abrupt steps in the submarine channel [G] that
435 resemble waterfalls, known as knickpoints. Indeed, observations of cable breaking events
436 worldwide show that although adjacent cables break, some cables can survive fast flows,

437 suggesting that uneven seabed erosion could be ubiquitous^{4,6,90}. It is not inevitable that a fast
438 turbidity current will break a cable. It is possible that cables that break are located close to
439 knickpoints, whereas cables that survive are located away from knickpoints^{4,5}. This theory
440 could be tested further by using time-lapse mapping. Understanding and predicting rates of
441 seabed erosion remains challenging, and it is critical for flow modelling, as patterns of
442 erosion or deposition could control flow behaviour⁹¹.

443

444 **[H1] How turbidity currents sculpt the seabed**

445

446 It is important to understand how turbidity currents form submarine canyons and channels or
447 how bedforms record flow states. Time lapse mapping of the seabed also provides new
448 insights into how turbidity currents interact with the seabed^{4, 17, 35, 38} and demonstrates
449 important ways in which turbidity currents differ from terrestrial rivers²⁵. For example, flows
450 exist in one of two basic states: **supercritical flow [G]**, which is thin and fast, or subcritical
451 flow, which is slow and thick. A critical Froude number (Fr) separates supercritical ($Fr > 1$)
452 from subcritical ($Fr < 1$) flow, with this Froude number being proportional to flow speed and
453 inversely proportional to the density contrast between the flow and the surrounding
454 medium⁹²⁻⁹⁵. Subcritical flows occur in most terrestrial rivers and produce bedforms such as
455 dunes and ripples that migrate down-slope. Turbidity currents are more prone to supercritical
456 flow than rivers, owing to their lower density contrast with the surrounding seawater than that
457 between river-water and air, and often faster speeds than rivers⁹²⁻⁹⁵. There is mounting
458 evidence that supercritical turbidity currents are widespread on the seafloor⁹⁶. For example,
459 spectacular trains of up-slope migrating bedforms have been mapped on submarine canyon
460 floors worldwide^{35,38,39}, on open continental slopes⁹⁶, and flanks of volcanoes⁹⁷. Combined
461 flow monitoring and time-lapse seabed mapping measurements suggest that these up-slope
462 migrating bedforms are linked to instabilities in supercritical flows^{38,50}, known as cyclic
463 steps. These instabilities can lead to repeated alternations of supercritical and subcritical
464 flows separated by hydraulic jumps that lead to formation of trains of up-slope migrating
465 bedforms⁹²⁻⁹⁵.

466

467 Time-lapse mapping is also showing how up-slope migrating knickpoints that are 10–30 m
468 high could dominate submarine channel-bend evolution^{98,99} (**Supplementary Fig. 2**).

469 Knickpoints can also occur in river channels. However, submarine knickpoints can move

470 faster and travel further than those in rivers, migrating hundreds of meters each year, driven
471 by overpassing turbidity currents^{98,99}. Knickpoints in rivers are formed by external processes
472 such as fault-uplift, sea-level variation and changes in bedrock. Whereas submarine
473 knickpoints are formed by internal processes such as cyclic steps or seabed loading and
474 failure⁹⁸. These seabed knickpoints excavate submarine channels and deposit sediment
475 downstream⁹⁸ (**Supplementary Fig. 2**). Knickpoints also have a key role in determining how
476 sediment, organic carbon and pollutants are shuffled in multiple stages to the deep-sea¹⁰⁰.

477

478 In meandering rivers, secondary (across-channel) flow at bends can sweep sediment towards
479 the inner-bank to form point bars²⁴. However, there has been vigorous debate on whether the
480 secondary flow in turbidity currents occurs, with near-bed flow towards the inner-bank of a
481 bend, as in rivers, or is reversed with near-bed flow towards the outer-bank^{24,101,102}. Flow
482 monitoring at a bend in the Congo Canyon suggests that two secondary flow cells occur, with
483 near-bed flow sweeping sediment towards the outer bend¹⁰³. But knickpoint migration might
484 be more important than secondary flow patterns for bend evolution, at least in some
485 settings^{98,100} (**Supplementary Fig. 2**).

486

487 Turbidity currents were first proposed to explain the origin of huge underwater canyons that
488 were discovered in the 1800s on ocean and lake floors^{1,104,105}. Currently available time-lapse
489 mapping only extends for ~25 years at most^{92,106}, but it is starting to help understand how
490 these canyons form. For example, time-lapse mapping of the Kaikōura Canyon offshore
491 Aotearoa New Zealand, before and after a major ($M_w = 7.8$) earthquake in 2016, shows that
492 the earthquake caused widespread failure of the canyon-rim and other areas¹⁷. This failure
493 produced a turbidity current that caused gravel waves to move down the canyon and eroded
494 $>1 \text{ km}^3$ of sediment, a volume that is 2–3 times larger than the amount of sediment that enters
495 the ocean annually from Aotearoa New Zealand rivers. This flow swept seabed life from a
496 canyon that previously had one of the highest benthic biomasses on Earth and carried ~7 Mt
497 of particulate organic carbon to the deep-sea¹⁷. Additionally, time-lapse mapping of the
498 Congo Canyon revealed that turbidity currents eroded $\sim 2.6 \text{ km}^3$ of sediment in one year and
499 flushed this sediment and associated organic carbon into the deep-sea⁴. These repeat surveys
500 show that fresh organic carbon from river floods can be transported rapidly to the deep-sea by
501 turbidity currents and explain how organic carbon can be efficiently buried by turbidity
502 currents with long runout and high flow speeds⁸.

503

504 Time-lapse measurements also show that canyon-flank collapse can produce landslide-dams
505 with implications for the transfer of sediment and organic carbon through canyons to the
506 deep-sea. For example, a $\sim 0.09 \text{ km}^3$ canyon-flank landslide dammed the Congo Canyon,
507 causing the temporary storage of a further $\sim 0.4 \text{ km}^3$ of sediment with $\sim 5 \text{ Mt}$ of (mainly
508 terrestrial) organic carbon¹⁰⁶. The trapped sediment was up to 150 m thick and extended
509 $>26 \text{ km}$ up the canyon from the landslide-dam, and this dammed sediment is currently being
510 eroded and gradually released¹⁰⁶.

511

512 Meter-scale resolution seabed surveys using autonomous underwater vehicles (AUVs) that
513 fly at just a few tens of meters above the seabed provide new insights into how submarine
514 channel and submarine fan systems operate^{35, 43, 52, 107-110}. Previous influential models of such
515 systems assumed that channels bifurcated down-slope at their terminations, to form a
516 distributary network, in the same way that many rivers bifurcate to create deltas¹¹¹. However,
517 AUV mapping of submarine channel mouth terminations shows that only a single main
518 channel is active, although there could be scours and bedforms, as well as adjacent headless
519 channels that are not connected to the main channel¹⁰⁹. This channel mouth geomorphology is
520 radically different to that seen in laboratory experiments¹¹², and its impact on flow processes
521 remains poorly understood.

522

523 **[H1] The formation of turbidity current deposits**

524

525 Ancient turbidity current deposits (turbidites) form rock sequences in numerous locations
526 worldwide, which can be kilometers thick, and accumulate over thousands to millions of
527 years^{111,113}. Geologists have used this rock record to propose models to describe how flows
528 and deposits are linked; however, such models are difficult to test without direct flow
529 observations⁸⁶. Therefore, direct measurements from active flows are now being combined
530 with analysis of seabed cores to directly demonstrate how deposits form a record of their
531 parent flow. These direct measurements can produce insights, albeit only for processes that
532 operate over short (days to a few years) time-scales, rather than longer term processes
533 occurring over thousands of years.

534

535 For example, observations of deposits from seabed cores were combined with time-lapse
536 mapping and direct flow measurements to show how trains of cyclic step bedforms created by

537 supercritical flows³⁸ are recorded in deposits⁵⁰. These measurements also showed that
538 individual flow deposits primarily composed of massive sand are linked to dense near-bed
539 layers. The up-slope migration of single bedforms initially produces backstepping stratal
540 geometries; however, these features were then eroded by the migration of subsequent
541 bedforms with complex and offset crests to leave complex nested scours^{50,114}.

542

543 Time lapse mapping has also been used to investigate the completeness of turbidite deposits,
544 and how much of the initially deposited sediment is finally preserved in the rock record. For
545 example, ~90 near-daily surveys spanning ~3 months (ref.³⁸) were used to map patterns of
546 erosion and deposition in the offshore Squamish Delta¹¹⁵. These surveys revealed that only
547 11% of the sediment deposits within channels was preserved, even on these very short
548 (3 month) time scales¹¹⁵. Seabed cores and moored traps that capture sediment from within
549 flows in Monterey Canyon were used alongside direct flow measurements to determine how
550 flows were linked to seabed deposits^{51,81,98}. This work showed that sand is restricted to a few
551 meters above the canyon floor, and internal tides that occur between turbidity currents stir up
552 fine-mud; therefore, fine-mud is poorly recorded in sand-dominated canyon floor cores⁵¹.

553 Organic carbon can also be kept in suspension by internal tides, such that it is
554 underrepresented in seabed cores⁸¹.

555

556 A puzzling feature of individual ancient turbidite beds is that they have a distinctly bimodal
557 distribution of thickness and internal deposit types¹¹⁶. Thicker (>40 cm) beds tend to contain
558 intervals of massive and planar-laminated sand, whereas thin beds (<40 cm) tend to comprise
559 only ripple cross-laminated sand and overlying mud¹¹⁶. Long distance mapping of individual
560 turbidite deposits shows that these deposits can evolve from thick to thin beds, with a
561 relatively sharp termination of massive and planar-laminated intervals comprising the thick
562 bed^{86,117}. Direct monitoring can now explain why turbidite deposits are bimodal⁴⁰; fast flows
563 contain a dense near-bed layer that deposits massive and planar-laminated sand, whereas
564 slow flows are entirely dilute and produce thinner turbidite deposits with cross-bedding⁴⁰
565 (**Fig. 6c,e**).

566

567 **[H1] Summary and future perspectives**

568 Detailed direct monitoring of turbidity currents has led to major advances in understanding,
569 including insights into the causes and frequency of turbidity currents, and their wider

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

578

579 There are now exciting opportunities to use direct monitoring data from turbidity currents to
580 test computational or analytical flow models, design more realistic laboratory flume
581 experiments, or understand deposits. These data indicate that models and flume experiments
582 should simulate near-bed layers with high (10–30%) sediment concentrations for fast
583 ($>1.5 \text{ m s}^{-1}$) flows. A key challenge is to develop a robust theoretical framework for how such
584 hyper-concentrated layers behave, in which turbulence is strongly damped, grain settling is
585 hindered, yet deposition occurs incrementally rather than en-masse. This framework would
586 be broadly comparable to that developed for even higher sediment concentration debris
587 flows¹¹⁸, in which en-masse deposition occurs.

588

589 This Review is also a rally call for widespread global monitoring of turbidity currents, over
590 longer timescales, that is underpinned by a new generation of sensors that are deployed at
591 substantially reduced cost and risk relative to present direct monitoring approaches. The
592 current situation in the field of turbidity currents is broadly comparable to trying to
593 understand how rivers work globally, using sporadic and incomplete monitoring from just
594 ~ 10 sites, mainly smaller streams. Further research is needed in locations where the
595 occurrence of turbidity currents would be more surprising, as shown by work in Whittard
596 Canyon⁶⁹ (**Supplementary Fig. 1**), or other types of system such as those with hyperpycnal
597 flows.

598

599 Present measurements are challenged by the fact that moored sensors are often broken by fast
600 ($>5 \text{ m s}^{-1}$) turbidity currents^{4, 119}; therefore, other types of sensors are needed that can be
601 placed outside of the active flow, and thus out of harm's way. Seismic signals¹²⁰ or acoustic
602 noise¹²¹ from turbidity currents could underpin a new generation of sensors that remotely
603 sense turbidity currents from a safe distance. Indeed, an exciting development is that

604 submarine landslides could also be remotely sensed using seismic signals, at low cost, over
605 large ocean basins. Such signals indicate that 75 of the 85 landslides that occurred in a 7-year
606 period in the Gulf of Mexico were triggered by remote and sometimes moderate earthquakes,
607 which were hundreds or even thousands of kilometers away¹²². Low cost sensing systems are
608 also needed that can relay data back through surface floats and satellites, rather than needing
609 to be retrieved by expensive vessels¹¹⁸. Without these low cost systems data will remain
610 limited to just a few sites.

611

612 Current direct monitoring techniques are good at measuring flow velocities. However, the
613 most important parameter might be the sediment concentration (and thus excess density
614 above that of surrounding seawater), as this density difference is what drives the flow¹, and
615 determines the sediment mass-flux. Future monitoring should focus on how to measure the
616 sediment concentration in turbidity currents, as well as how flows erode the seabed, as mass-
617 exchange with the bed often dominates the overall flow behaviour⁹¹. Methods to constrain
618 mass fluxes, together with a more global monitoring network could determine the global
619 sediment and organic carbon fluxes carried by turbidity currents, and their fundamental
620 controls, making it possible to explore how these fluxes compare to other major global
621 sediment and carbon pumps on Earth (**Fig. 2a-c**).

622

623

624

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931

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943

944 **Author contributions**

945 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.
946 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.
947

948 **Competing Interests**

949 The authors have no competing interests.

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953 **Supplementary information**

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955
956

957 **Key Points**

- 958 • Previously, submarine turbidity currents were thought to be impractical to monitor in
959 action, mainly owing to their ability to damage sensors in their path, but detailed
960 monitoring is now possible, and it is revealing major new insights.
- 961 • Direct monitoring is identifying triggers for flows, such as very dilute river plumes,
962 and consistently shows that turbidity currents occur much more frequently than
963 predicted by past models such as, sequence stratigraphic models.
- 964 • Owing to turbidity currents, the global burial efficiency of terrestrial organic carbon
965 (28–45%) in marine sediments is substantially higher than previous (10–30%)
966 estimates, and even higher (>60–80%) during glacial low-stands.
- 967 • Fast (>1.5 m s⁻¹) turbidity currents are driven by a dense (10–30% concentration)
968 near-bed layer at their front, which must be included in flow models, whereas slower
969 flows are entirely dilute.

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

976

977 **Glossary**

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

980

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

983

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

986

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

989

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

993

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

997

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

1000

1001 *Supercritical flow:* Flows can exist in two basic states that are either thin-and-fast
1002 ('supercritical') flow or thick-and-slow ('subcritical') flow, which are separated by a
1003 hydraulic jump.
1004

1005 *Submarine fan:* A large-scale accumulation of sediment formed by turbidity currents that
1006 comprises a canyon, channel with levees (upraised flanks of a submarine channel that lie
1007 above the surrounding seafloor formed by the overspill of turbidity currents from the
1008 channel), and a lobe (a region that lies beyond the end of a submarine channel, where
1009 turbidity currents expand, often characterised by unusually rapid sediment deposition and
1010 scours).
1011

1012 *Submarine canyon:* A valley that is deeply incised into the seafloor through which turbidity
1013 currents flow, which is much deeper than a submarine channel.
1014

1015 *Submarine channel:* A channel that is less deeply incised into the seafloor than canyons
1016 through which turbidity currents flow, whose upraised flanks (called levees) can lie above the
1017 surrounding seabed.
1018

1019 *Remineralisation:* The process by which organic carbon is turned into CO₂.
1020

1021 *Varve:* A thin layer of fine sediment that represents the deposit of a single year within a lake.
1022

1023 **Figures**

1024

1025 **Figure 1. Comparison between turbidity currents and other major global sediment**
1026 **transfer processes. a** | The distances that flows travel and their velocities. **b** | Mass of
1027 sediment carried by individual events (red), and as annual sediment mass fluxes (black), with
1028 the grey bars showing the uncertainty. The sediment mass carried by the Grand Banks
1029 turbidity current in 1929 (ref.³) and Congo Canyon turbidity currents in 2020 (ref.⁴) are
1030 shown by the blue and green dotted lines respectively. Supplementary Table 1 provides
1031 further information and lists the source literature used for the distances, speeds, masses or
1032 annual mass fluxes. These data show that turbidity currents are one of the most important
1033 sediment transfer processes ('pumps') on Earth.

1034

1035 **Figure 2. Turbidity currents have a globally important role in organic carbon burial. a** |
1036 Global sediment mass fluxes (see Figure 1 and Supplementary Table 1 for original data
1037 sources). **b** | Global organic carbon mass fluxes. A future challenge will be to quantify global
1038 sediment and organic carbon fluxes in turbidity currents¹⁴. An estimated 62–90 Mt yr⁻¹ of
1039 terrestrial organic carbon is buried in marine sediments by turbidity currents¹⁴. **c** | Pathways
1040 for global organic carbon cycling. The burial of organic carbon by turbidity currents affects
1041 the atmospheric partial pressure of CO₂ (pCO₂) and thus climate over long term (>1 ka) time
1042 scales. The black and blue arrows indicate the terrestrial organic carbon pathways and marine
1043 organic carbon pathways, respectively. Processes that exchange carbon with the atmosphere
1044 on short term (<~100 yr) timescales are shown by the purple arrows. **d** | The burial of organic
1045 carbon by turbidity currents can be highly efficient, such as within the huge Bengal
1046 Submarine Fan⁸. Organic carbon types and amounts in river samples (white stars) resemble
1047 those in deep-sea cores⁸ (red stars). Part d is from ref.¹²³, Springer Nature Limited, and
1048 modified using data from GEBCO_2021 Grid, www.gebco.net.

1049

1050 **Figure 3. Direct monitoring of turbidity currents. a** | Map of the 12 locations (red stars)
1051 worldwide where turbidity currents have currently been monitored in detail^{27-54,61,69, 124-125} and
1052 other key locations (yellow circles) mentioned in this Review. **b,c,d** | Flow monitoring has
1053 moved from **(b)** small systems in shallow water such as the Squamish Delta^{38-39,50,59,60,115}
1054 where logistics are easier, to **(c)** larger systems in moderate depths such as in Monterey
1055 Canyon^{34,35,51-52,61,87}, and **(d)** finally to very large systems in deep-water such as the Congo

1056 Fan, where turbidity currents broke the West Africa Cable System (WACS) and South
1057 Atlantic (SAT-3) telecommunication cables (dotted lines) in 2020 and 2021 (ref.^{4,36,37}). **e** | An
1058 acoustic Doppler current profiler (ADCP) mooring on the deck of a research vessel before it
1059 was deployed in Congo Canyon. Such moorings are used to monitor the flow, with the ADCP
1060 housed in a buoyant float connected to a heavy anchor (weighing approximately 1 tonne)
1061 through a wire or chain, and recovered by remotely triggering an acoustic release¹⁹. **f** | A
1062 heavy frame weighing 800 kg that slid for ~7 km down Monterey Canyon at speeds of up to
1063 4.4 m s⁻¹ (ref.^{35,52}). It moved at a similar speed to much smaller and lower density objects,
1064 suggesting that these objects were rafted when entombed in a dense near-bed layer of
1065 sediment.

1066

1067 **Figure 4. Insights into the causes of turbidity currents. a** | Four main causes of turbidity
1068 currents^{55,56} are slope failures (landslides); plunging of hyperpycnal river plumes that are
1069 denser than seawater owing to the high sediment concentrations⁵⁷; sediment settling from
1070 surface river plumes^{39,47-48,58}; and oceanographic processes such as storm waves, tides and
1071 internal waves that can supply sediment to canyon heads and trigger flows (including through
1072 landslides). **b** | There can be substantial delays between periods of rapid sediment
1073 accumulation in canyon heads, and the final triggering of turbidity currents by subtle external
1074 triggers^{4,60-61}. **c,d** | River floods and tides combine to generate turbidity currents at many sites
1075 worldwide, including four extremely powerful turbidity currents (red stars) that flushed the
1076 Congo Canyon in 2020–2022 (ref.^{4,5}). These canyon-flushing turbidity currents are associated
1077 with major floods along the Congo River, but occurred several weeks to months after the
1078 flood peaks, often at spring tides^{4,5}. The tidal coefficient is the size of the tide in relation to its
1079 mean. Parts c and d are adapted from ref.⁴, Springer Nature Limited.

1080

1081 **Figure 5. Submarine fans and frequency of turbidity current activity. a** | Summary of the
1082 main elements of a submarine fan. **b** | Sedimentation rates in different parts of the Congo
1083 Submarine Fan¹²⁶. **c** | At glacial low-stands in sea-level, most river mouths are directly
1084 connected to the submarine canyon-head^{67,68}, meaning that the turbidity currents are highly
1085 active^{66,70}. There are a small number of modern canyon-heads that are highly active because
1086 they still connect directly to river mouths, such as the Congo Canyon⁴ or Gaoping Canyon
1087 ^{9,41,42}. **d** | Previous models (such as sequence stratigraphic models) proposed that submarine
1088 canyons are dormant during high-stands in sea-level⁶⁶, because river mouths are separated
1089 from most canyon heads. **e** | There is an emerging view that turbidity current systems are

1090 surprisingly active during the present day high-stand in sea-level⁷⁰ because sediment can also
1091 be transferred efficiently across the shelf by waves or tide action to the canyon head^{73,74}, or
1092 through the progradation of large clinofolds⁷².

1093

1094 **Figure 6. Insights into the internal structure of turbidity currents. a** | Velocity time-
1095 series of a turbidity current in Congo Canyon measured with an Acoustic Doppler current
1096 profiler (ADCP) mooring. **b** | Summary of the velocity structure of turbidity currents in
1097 Congo Canyon, comprising a near-bed frontal zone (frontal cell) that is faster and denser than
1098 the rest of the flow (inset), and runs away from a trailing body and tail, causing the flow to
1099 stretch³⁶. **c-e** | Time-series of velocity and layer-average sediment volume concentration
1100 derived using the Chezy equation of the three types of turbidity currents observed in Bute
1101 Inlet. Type 1 flows (**c**) have a frontal cell with a fast ($>1.7 \text{ m s}^{-1}$) and dense near-bed layer, as
1102 in Congo Canyon flows, which drives the event and dominates sediment flux⁴⁰. Type 2 flows
1103 (**d**) have intermediate speeds and sediment concentration. Type 3 flows (**e**) are slow, entirely
1104 dilute, and lack a dense and fast frontal layer. A single turbidity current can evolve from Type
1105 1 to Types 2 and 3 as it decelerates⁴⁰. The right inset shows the inferred types of turbidite
1106 deposit likely formed by different types of flow, with Bouma sequence intervals (T_A to T_E)
1107 marked⁴⁰. Parts a and b are adapted from ref.³⁶, CC BY 4.0. Parts c,d and e are adapted from
1108 ref.⁴⁰, CC BY 4.0.

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1111 **Figure 7. A new view of how turbidity currents behave. a,b,c** | Past models inferred that
1112 flows either **a** | deposited sediment and dissipated; **b** | eroded, became denser and faster, and
1113 accelerated (ignited); or **c** | balanced erosion and deposition to create a near-equilibrium
1114 uniform velocity (autosuspending) state²⁵. Red arrows denote flow speed; black arrows
1115 indicate sediment exchange with the bed. **d** | Summary of the changes in flow front speeds
1116 observed with direct field measurements, illustrating three key points. (1) Flow behaviour
1117 diverges depending on whether the initial speed exceeds the threshold speed of $4\text{--}5 \text{ m s}^{-1}$
1118 (ref.^{4,87}). Above this threshold, flows accelerate or sustain their speed, and travel for longer
1119 distances. Flows that are initially slower than this threshold decelerate and dissipate. This
1120 threshold speed is independent of the dominant sediment grain size. (2) After initial ignition–
1121 autosuspension flows with similar front speeds can runout for highly variable distances, and
1122 erode to very different degrees. (3) Small changes in flow front speeds occur over long
1123 distances; sometimes despite flows eroding large sediment volumes. **e** | New ‘travelling

1124 wave' model in which flows can both erode the seabed (as in ignition) and sustain near
1125 uniform speeds for long distances^{4,87} (as in autosuspension). The flow contains a dense
1126 frontal layer in which seabed erosion is balanced by sediment shed back into a dilute trailing
1127 body. Part d is adapted from ref.⁴, Springer Nature Limited.

1128

1129 TOC blurb:

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1132 Seafloor turbidity currents form Earth's largest sediment accumulations, deepest canyons and
1133 longest channels, but their destructive nature makes them notoriously difficult to measure in
1134 action. This Review explores how insights from detailed direct measurements have advanced
1135 understanding of turbidity currents.

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