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## What determines the downstream evolution of turbidity currents

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#### 25 Abstract:

Seabed sediment flows called turbidity currents form some of the largest sediment accumulations, 26 deepest canyons and longest channel systems on Earth. Only rivers transport comparable 27 sediment volumes over such large areas; but there are far fewer measurements from turbidity 28 29 currents, ensuring they are much more poorly understood. Turbidity currents differ fundamentally from rivers, as turbidity currents are driven by the sediment that they suspend. Fast turbidity 30 currents can pick up sediment, and self-accelerate (ignite); whilst slow flows deposit sediment 31 32 and dissipate. Self-acceleration cannot continue indefinitely, and flows might reach a nearuniform state (autosuspension). Here we show how turbidity currents evolve using the first 33 detailed measurements from multiple locations along their pathway, which come from Monterey 34 Canyon offshore California. All flows initially ignite. Typically, initially-faster flows then 35 achieve near-uniform velocities (autosuspension), whilst slower flows dissipate. Fractional 36 37 increases in initial velocity favour much longer runout, and a new model explains this bifurcating behaviour. However, the only flow during less-stormy summer months is anomalous as it self-38 accelerated, which is perhaps due to erosion of surficial-mud layer with fine sands mid-canyon. 39 40 Turbidity current evolution is therefore highly sensitive to both initial velocities and seabed character. 41

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Keywords: Turbidity current; submarine canyon; ignition; dissipation; autosuspension; flowbehaviour

#### 46 1. Introduction

47 Seafloor sediment density flows (called turbidity currents) are the dominant global mechanism for transporting sediment from the continental shelf to the deep sea. These flows play a crucial 48 role in global organic carbon burial and geochemical cycles (Galy et al., 2007), and supply of 49 50 nutrients to deep-sea ecosystems (Canals et al., 2006). Only rivers transport sediment over comparable areas, although one turbidity current can carry more sediment than the annual flux 51 from all the world's rivers combined (Talling et al., 2013). Powerful turbidity currents can badly 52 damage seafloor infrastructure, including oil and gas pipelines, and telecommunication cable 53 networks. The latter carry over 95% of global data traffic (Carter et al., 2014), forming the 54 55 backbone of the internet and financial markets. Turbidity current deposits host valuable oil and gas reserves, and form thick sequences of ancient rocks that record Earth's history (Nilsen et al., 56 2008). The downstream evolution of velocities and runout lengths controls how sediment is 57 dispersed, the resulting deposit character and shape, and hazards to seafloor infrastructure. It is 58 thus important to understand how turbidity currents work, especially what controls their runout, 59 and changes in flow velocity with distance. 60

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Turbidity currents differ profoundly from terrestrial rivers; unlike rivers they are driven by the 62 63 weight of sediment they carry, and this sediment can be entrained or deposited onto the seafloor along turbidity current pathways. Previous work suggested that exchange of sediment with the 64 seabed may lead to positive feedbacks, such that turbidity current behaviour is inherently 65 66 unstable and diverges (Fig. 1) (Bagnold, 1962; Parker, 1982). These studies proposed that flows which erode sediment become denser, and thus accelerate, causing increased erosion, and further 67 acceleration (Fig. 1a). This process is called ignition, and it may play a pivotal role in producing 68 powerful and long runout flows. Conversely, flows that deposit sediment may decelerate, leading 69

to further deposition ('dissipation'; Fig. 1b). Such positive feedbacks may produce thresholds in 70 71 behaviour that depend on small differences in initial flow state. It has also been proposed that flows could achieve a near-uniform state in which erosion is balanced by sediment deposition, 72 73 termed autosuspension (Fig. 1c, d) (Pantin, 1979). Here, turbulence within the flow is strong 74 enough to keep particles in suspension, and counteracts their settling velocity (Parker, 1982). 75 However, unlike ignition, there is no net gain of sediment from the bed, as the bed is too hard to erode (Fig. 1c), or sediment erosion balances sediment deposition during autosuspension (Fig. 76 1d). Flows that balance erosion and deposition will tend towards spatially uniform velocities, 77 assuming that seabed gradient and flow width do not change markedly. Self-acceleration due to 78 79 ignition is unlikely to continue indefinitely: increased sediment concentrations will eventually damp the turbulence that keeps sediment aloft (Baas et al., 2009) and shield the bed from rapid 80 erosion, or increase frictional drag and thus reduce flow velocities. However, there is 81 82 considerable debate over what happens after ignition ceases (Fig. 1a). Do the flows reach a state of autosuspension; and if so, what do autosuspending flows look like? In particular, do flows 83 develop a dense near-bed layer that drives the event (as proposed by e.g. Winterwerp, 2006), or 84 remain an entirely dilute and fully turbulent suspension (e.g. Cantero et al., 2012)? 85 86

Turbidity currents are notoriously difficult to monitor in action, due to their location, episodic occurrence, and ability to damage instruments in their path (Inman et al., 1976; Talling et al., 2013). Consequently, there are very few direct measurements from oceanic turbidity currents, ensuring fundamental theories on how turbidity currents work are poorly tested. In particular, ignition and autosuspension have been difficult to reproduce in laboratory experiments (Southard and Mackintosh, 1981). This may be because most laboratory experiments are relatively slow moving, compared to full-scale oceanic flows, and thus have limited ability to erode their

substrate, or fully support sediment with realistic grain sizes. Experimental flows thus tend to 94 95 dissipate. Sequeiros et al. (2009, 2018) successfully produced self-accelerating turbidity currents in relatively slow moving (< 20 cm/s) laboratory experiments with low density particles, but they 96 did not reproduce fully realistic processes of seabed erosion. However, new technologies have 97 recently led to major advances in monitoring of active turbidity currents (Hughes Clarke, 2016). 98 99 This includes acoustic Doppler current profilers (ADCPs) that measure velocity profiles to within a few meters of the seafloor (Xu, 2010). Here we use ADCP and other sensor data to observe 100 spatial patterns of flow ignition, dissipation, and autosuspension in unprecedented detail; and to 101 study how flows work in general. 102

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This study analyses the most detailed (7 locations at sub-minute intervals) field measurements yet 104 from oceanic turbidity currents, which include the fastest (up to 7.2 m/s) flows captured via 105 106 moored instruments. These measurements come from the upper 52 km of Monterey Canyon, offshore California (Fig. 2a) (Paull et al., 2018). Previous direct monitoring of turbidity currents 107 108 has typically involved measurements at a relatively small number ( $\leq$ 3) of locations along their 109 pathway, which provides limited information on how flows behave (Khripounoff et al., 2009; Liu 110 et al., 2012; Azpiroz-Zabala, 2017). By having measurements in seven locations along a turbidity current pathway we are able to determine how flows evolve. Here we focus on changes in the 111 average flow front velocities between measurement locations (termed transit velocities), 112 maximum internal velocities, as well as duration of flow velocities in each event (as measured by 113 114 ADCPs).

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116 **1.1. Aims** 

The first aim is to document changes in turbidity current velocity and runout distance, and hence 117 118 flow behaviour. What is the observed pattern of ignition, autosuspension and dissipation; and do multiple flows show a consistent pattern of behaviour? The second aim is to understand what 119 120 causes these patterns of flow behaviour. In particular, we consider how two factors (initial 121 velocity and substrate erodibility) affect flow behaviour, and how near-uniform flow (autosuspension) may follow ignition. Our third aim is to determine if broadly similar flow 122 behaviour is seen elsewhere, although suitable field data are sparse. Our fourth aim is to compare 123 these field observations to most widely accepted theories for ignition and autosuspension. To 124 what extent do these new field data provide a test of past theories? Finally, we develop a new 125 126 generalised model for how turbidity currents in submarine canyons floored by loose sand operate, which better explains these novel field observations. 127

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#### 129 **1.2.** Terminology

130 *Turbidity current* is used here as a general term for all types of submarine sediment density flow. Dense flow signifies sediment concentrations that are high enough to damp turbulence 131 132 significantly, such that turbulence is no longer the main support mechanism, whilst *dilute flow* is 133 fully turbulent. There is no single threshold value for sediment concentration at which turbulence is strongly damped, as this depends on multiple factors including flow velocity, sediment 134 135 mineralogy and grainsize. But dilute flows typically have sediment concentrations of << 1%, 136 whilst dense flows might often contain > 10% sediment by volume. *Diverging* behaviour denotes 137 how small changes in initial flow velocity are linked to large changes in subsequent runout. It 138 does not imply that flow behaviour is bimodal, and intermediate runout lengths can still occur.

#### 140 2. Material and Methods

141 The Coordinated Canyon Experiment (CCE) monitored the upper 50 km of Monterey Canyon (California, USA) to water depths of 1850 m, for 18 months from 2015 to 2017 (Fig. 2) (Paull et 142 al., 2018). Sand is primarily delivered to the canyon head via longshore drift, with little river 143 144 input (Paull et al., 2005). The entire canyon-channel system extends for over 300 km, but flows that runout for over 60 km, to a water depth of 2,850 m, only occur every few hundred years 145 (Stevens et al., 2014). Flows are confined, and experience a constant seafloor gradient and width 146 in the upper part of Monterey Canyon (Fig. 3). The upper Monterey Canyon, up to 2100 m water 147 depth, has a sinuosity of 1.9 (Paull et al., 2011). The canyon briefly narrows at a constriction 148 between 1300 and 1400 m water depth, called the Navy Slump (Figs. 2 and 3) (Paull et al., 2011). 149 This study uses data recorded by ADCPs along the canyon thalweg (Fig. 2), which were part of a 150 larger instrumental array (Supplementary fig. 1) (Paull et al., 2018). 151

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#### 153 2.1. ADCP measurements

154 ADCPs documented velocity profiles through the turbidity currents (Fig. 3; Supplementary Fig. 1), although they are typically unable to make measurements within a few meters of the bed. The 155 156 shallowest five mooring stations (MS1 to 5), and deepest mooring station (MS7), had downwardlooking 300 kHz ADCPs located approximately 65 m above the bed seafloor (Paull et al., 2018). 157 158 ADCPs on these moorings recorded velocity at 30 second intervals. A Seafloor Instrument Node 159 (SIN) was located between MS5 and MS7, which contained three separate upward-looking 160 ADCPs recording at 10 second intervals, using acoustic sources with three different frequencies 161 (300, 600, 1200 kHz). No reliable ADCP measurements of current velocity are available from the 162 shallowest mooring (MS1) for some flows, as this mooring broke loose on January 15, 2016 163 (Paull et al., 2018).

#### 2.2. Maximum flow velocity measured by ADCPs 165 166 Determining the maximum reliable velocity measured by the ADCP is not straightforward. The arrival of an event is accompanied by mooring tilt and high near-bed sediment concentrations, 167 168 influencing the ability of ADCPs to accurately record velocities (Paull et al., 2018). Side-lobe 169 interference may compromise some ADCP measurements within 1-3 m of the seabed (Teledyne RD Instruments, 2011), although this depends on the relative strength of backscatter from side-170 171 lobe areas and sediment in the flow. We thus adopted a consistent procedure for calculating 172 maximum ADCP-measured velocities, which excludes the 20 highest values during an event. The overall trend of internal velocities remains the same, and therefore our ADCP data processing 173 does not change this paper's main conclusions. 174 175 176 2.3. Transit velocities and runout distance Flow arrival times at the 6 ADCP moorings and SIN were used to measure transit velocities, 177 which are average front velocities across distances between 0.5 km and 15 km (Fig. 3a). Arrival 178 179 times are based on 30 second (or 10 second for SIN) recording interval of the ADCPs, corrected for clock drift. Distances between sensors were measured along the canyon thalweg, based on a 180 15 m bathymetric grid. It is assumed that flows principally followed the thalweg (Fig. 2a). 181

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#### 183 **2.4.** Duration of powerful flow measured by ADCPs

As frontal or maximum velocities only tell part of how flow is evolving, and changes in velocity
structure, the duration of a fast-moving flow is also quantified and presented (Table, 1;

186 Supplementary fig. 4). This duration, determined for three different velocity thresholds, provides187 an additional indication of how flows may lengthen or stretch over time.

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#### 189 **2.5.** Canyon topography

Seafloor gradient is determined along a midline through the canyon thalweg (Fig. 3b), using an average of 10 grid-cells, each of which has a length of 15 m. Canyon width is defined using the area of active bedforms (Paull et al., 2018), and measured every 200 m down the canyon. The canyon floor is delimited by steep canyon walls with slopes of ~10 to 45°.

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#### 195 **2.6.** Grain sizes

Sediment traps were mounted at 10 meters above the seafloor on moorings (Supplementary fig.
1). They were tilted and brought closer to the bed by the initial powerful stages of some flows.
Grain sizes in sediment traps from the upper canyon (MS1, MS2, and MS3) were used for most
events. For the September 1<sup>st</sup> event, MS3 and MS4 are used, as the event ignited farther down in
the canyon. Laser particle grain size measurements were taken every 1-5 cm from traps. Discs
released automatically into the traps at 8-day intervals provided time markers. Supplementary fig.
5 shows grain size distribution for the flow events, including mean grain sizes used for Fig. 6.

#### 203 **3. Results**

The entire sensor array in Monterey Canyon recorded 15 flows (Paull et al., 2018). Here we consider only the 13 flows measured using the moored ADCP array (Fig. 2b; Supplementary figs. 1 and 2), as we rely on ADCP measurements. Twelve of these 13 ADCP-measured flows started in the upper canyon at water depths of < 300 m. Flows were measured first by ADCPs at Mooring Station (MS) 1, located 6.7 km from the canyon head (Figs. 2a and 3a). Many flows

then rapidly dissipated, including six flows that died out entirely before MS2, which is 9 km 209 210 downstream of MS1 (Fig. 3a). Of the seven flows measured at multiple moorings, three flows 211 terminated within the sensor array. One event occurred only in the mid-canyon, between MS4 212 and MS5. Three further flows swept through the entire sensor array, running out for over 50 km 213 from the canyon head, although they had very different velocities and durations at the final sensor site (Fig. 4). Most (12 of 13) flows were initiated during the winter months (Fig. 2b), during 214 which time storm waves are most pronounced and are thought to be important for flow initiation 215 216 (Paull et al., 2018). Only one event occurred in the summer months. This event on September 1<sup>st</sup> 2016 did not coincide with large wave heights, a river flood, or earthquake; suggesting another, 217 as yet poorly understood, trigger (Paull et al., 2018). 218

219

220 Transit velocities are available for the seven flows that reached multiple moorings (Fig. 3a). The 221 transit velocities between the first two moorings (MS1 and MS2) have broadly similar values of between 4 and 6 m/s. The runout length of these flows varied greatly, with large increases in 222 223 runout length correlating with only slightly faster initial frontal velocity (Fig. 3a). However, one 224 event recorded during the CCE experiment showed a different trend, and it was the only event occurring outside the winter months, on September 1<sup>st</sup> (Fig. 1b). This event started with an initial 225 comparatively low frontal velocity between MS1 and MS2 of ~4 m/s, identical to the initial 226 frontal velocity of the November 24<sup>th</sup> event (Fig. 1c) (Paull et al., 2018). However, the November 227 24<sup>th</sup> event failed to reach MS3; whilst the September 1<sup>st</sup> event accelerated between MS3 and 228 229 MS5, and reached the end of the instrument array (Fig. 3a).

230

The maximum ADCP velocities measured within flows occurred within the first 10 minutes ofthe flow front arrival. These internal velocities show a broadly similar pattern to the transit

velocities (Fig. 3a). Flows with slower maximum ADCP-measured velocities at the first mooring
tended to die out abruptly in the upper canyon, whilst events with faster ADCP-measured
velocities ran out for much longer distances (Fig. 3a). Note that ADCP measurements define six
shorter runout events that are only recorded at one mooring, and thus lack transit velocity data.

238 Flow behaviour is only partly captured by transit and maximum ADCP measured velocities. For example, modest increases in transit velocity are often associated with more prolonged periods of 239 240 powerful flow (Fig. 4, Table 1). As a powerful flow is more efficient in entraining substrate, the duration of powerful flow is important for ignition or autosuspension. Flows tend to stretch, as 241 the frontal part of the flow runs ahead from the slower moving body and tail (Fig. 4) (Azpiroz-242 Zabala, 2017). Overall, long run-out events occurring in winter tended to significantly stretch, 243 such that they extended for almost the entire length of the instrument array. Shorter winter events, 244 based on data from the shorter winter event on November 24<sup>th</sup>, are initially ~10 km in length as 245 the event arrives at MS2, but die out in the upper-canyon. The long runout summer event was 246 initially weak, but became much more prolonged and faster mid-canyon, as well as increasing its 247 248 transit velocity; before dissipating rapidly between MS5 and MS7 (Fig. 4). Most flows started with a flow front thickness <10m. The long run-out events in winter developed thicknesses >30 249 250 m (Fig. 4) (Paull et al., 2018).

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#### 252 **4. Discussion**

#### 4.1. Is there a consistent pattern of behaviour for turbidity currents?

Eleven of the twelve flows show a broadly consistent pattern of runout behaviour, which can be based on the initial transit velocity between the first two moorings, and the maximum ADCP-

measured velocities at the first mooring (Fig. 3a). Flows with the fastest initial velocities tend to 256 257 run out further. However, small changes in initial transit velocities, or maximum ADCPmeasured velocities, lead to much larger changes in runout distance and subsequent flow 258 velocity. Runout distances are thus highly sensitive to initial velocities, leading to diverging flow 259 260 behaviour (Fig. 3a). All flows initially accelerate, and the initially fastest flows have nearuniform transit velocities for several tens of kilometres and can stretch up to 35 km in length (4). 261 Flows with only fractionally slower (~0.5 m/s) initial transit velocities, or maximum ADCP-262 measured velocities, die out mid-canyon. The six slowest moving flows at MS1 terminate rapidly 263 before reaching MS2 (Fig. 3a). These flows that die out in the upper or mid-canyon are initially 264 265 powerful, and can sometimes carry heavy (800 kg) objects, or move moorings down-canyon, at velocities of  $\geq 4$  m/s, but their power does not persist for several kilometres. Only the fastest 266 flows at the first mooring maintain their velocity for longer distances, and lengthen significantly. 267 The single exception to this general pattern of behaviour (Figs. 2c and 3) occurred on September 268 1<sup>st</sup> 2016. This flow's transit velocity and maximum ADCP-measured velocity increased in the 269 mid-canyon (Fig. 3a), and the duration of powerful flow lengthened markedly (Fig. 4). 270 271 272 These field data thus provide new insights into where and how flows ignite, dissipate or 273 autosuspend. A notable observation is that the four most powerful flows at MS1 have near-

uniform transit velocities for ~20-35 km, from MS1 to MS3; and near-uniform maximum internal
(ADCP-measured) velocities from MS1 to MS2 (Fig. 3a). This suggests that an initial phase of
acceleration (ignition) is followed by near-uniform flow velocities (autosuspension), at least near
the flow front. Transit velocities are averages over substantial distances, and internal (ADCPmeasured) velocities come from a few specific locations. Thus, it is possible that flow velocities

show greater localized variability than depicted in Fig. 3a. However, available field data indicate
near-uniform transit velocities (autosuspension) over substantial distances.

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#### 282 **4.2.** What factors control turbidity current behaviour?

We now seek to understand what controls these patterns of flow behaviour. Twelve flows 283 284 accelerated rapidly from rest within the upper 6.7 km of the canyon, reaching velocities of at least 3 to 6 m/s at MS1 (Fig. 2). These turbidity currents were most likely generated by seabed failure, 285 286 typically during storm events, as sediment plumes from rivers are weak or absent (Paull et al., 287 2018). An initial phase of acceleration will partly result from gravitational acceleration of the failed mass, but it may also indicate that flows eroded the seabed and self-accelerated (ignited). 288 However, the relative importance of simple gravitational acceleration of an initial failure, and 289 ignitive self-acceleration via subsequent seabed erosion, is uncertain due to a lack of repeat 290 291 bathymetric surveys with high enough frequency upstream of MS1.

292

293 Beyond MS1, small (< 0.5-1 m/s) increases in initial transit or maximum ADCP-measured velocities are associated with profound differences in subsequent flow behaviour (Figs. 2c and 3). 294 295 We thus infer that initial velocities in the upper canyon determine later flow behaviour. Flows with only fractionally higher initial transit velocities, or maximum internal ADCP-measured 296 297 velocities, tend to run out for much greater distances (Fig. 3a; Table 1). This strongly diverging 298 flow behaviour is not due to changes in seafloor gradient or canyon width, as canyon axial channel width (~200 m) and gradient (~ 2°) are relatively uniform from MS1 to MS3 (Fig. 2d, e), 299 300 and all of these flows experienced similar changes in canyon slope and width. However, the 301 axial channel widens significantly beyond MS3 (from ~200 to ~600 m), which may explain why 302 most flows consistently decelerate beyond MS3 and MS4 (Fig. 3).

increased mid-canyon (Fig. 3a), and the duration of powerful flow velocities increased (Fig. 4; 305 306 Table 1). This acceleration is not related to steepening or narrowing of the canyon, and cannot be 307 explained by a 'tail wind' from internal tides (Supplementary Fig. 3). This flow was also the only event to occur in summer (Fig. 2b). One hypothesis is that self-acceleration of the September 1<sup>st</sup> 308 event resulted from entrainment of a surficial-mud layer, deposited during less-stormy summer 309 months. Surficial-mud layers that are 1-12 cm thick occur in the nearby La Jolla Canyon (Paull et 310 311 al., 2013), whilst mud layers in cores from MS7 in Monterey Canyon are 1-3 cm thick, with modal grain sizes of ~50-80 µm (Fig. 8 of Maier et al., 2019). However, it is not clear whether 312 surficial-mud layers are better developed during summer months, as information from repeat 313

coring during different seasons is lacking. Moreover, strong (50-80 cm/s) internal tides in
Monterey Canyon rework canyon floor mud throughout the year (Maier et al., 2019). An
alternative hypothesis for mid-canyon ignition of the September 1st event is triggering of a local
substrate failure, forming a knickpoint. Such knickpoints are observed in several places on the
canyon floor, and they have been termed 'master head scarps' in past work (Paull et al., 2010).
However, we also lack suitably detailed time-lapse seabed surveys from the mid-canyon to
determine whether a local knickpoint failure occurred.

The September 1<sup>st</sup> event is anomalous, as it was initially slow moving but its transit velocity then

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#### 322 **4.3.** Do submarine flows in other locations show similar behaviour?

Having determined that there is a consistent pattern of flow behaviour in Monterey Canyon, albeit with one exception, we now seek to understand if similar behaviour occurs elsewhere, and is thus of more general importance. There are few other locations worldwide where the transit or

326	internal velocities of oceanic turbidity currents have been measured at more than 4 locations
327	along the flow pathway. Indeed, we are aware of only 3 such datasets (Fig. 5).

329	One of these field datasets comes from cable breaks along Gaoping Canyon, offshore Taiwan,
330	which (unlike Monterey Canyon) is fed by a major river mouth (Fig. 5b) (Gavey et al., 2017).
331	Seabed gradients along Gaoping Canyon (0.3°-1.0°; Gavey et al., 2017) are somewhat lower than
332	Monterey Canyon (1.6°- 2.3°; Paull et al., 2011) (Fig 5). Transit velocities in Gaoping Canyon
333	are nearly constant for ~100 km, suggesting that the turbidity currents reach a near-uniform
334	equilibrium state. This pattern of uniform flow front velocities (autosuspension) is thus not
335	specific to Monterey Canyon, and it may persist over even longer distances.
336	
337	A second data set comes from a turbidity current that broke submarine cables offshore from the
338	Grand Banks, Newfoundland, in 1929 (Heezen and Ewing, 1952; Piper et al., 1988). The
339	turbidity current resulted from extensive but thin (average 5 m) failures on the continental slope,
340	with ~ 185 km <sup>3</sup> of sediment deposited on the Sohm Abyssal Plain (Piper and Aksu, 1987; Piper et
341	al., 1988). These failures progressively entrained seawater and evolved into debris flows, and
342	then turbidity currents (Piper et al., 1999). Flow was confined initially within multiple valleys for
343	the first ~500 km of the pathway (Hughes Clarke et al., 1990), where it reached a transit velocity
344	of 19 m/s on a gradient of ~ $0.5^{\circ}$ (Hughes Clarke et al., 1988). This initial phase of the flow
345	eroded the seabed, and may have ignited; although this is not demonstrated by flow velocities
346	from cable breaks. Transit velocities then decreased to 6.2 m/s on gradients of ~0.15 to $0.05^{\circ}$ , as
347	flow became poorly confined, and spread to become several hundred kilometres wide (Fig. 5c;
348	Heezen and Ewing, 1952; Hughes Clarke, 1988; Hughes Clarke, 1990; Piper and Hundert, 2002).

Its transit velocity continuously decreased with distance during these later stages, showing howreduction in confinement can control flow behaviour, leading to dissipation.

351

# 4.4. Comparison of field data to previous theory of autosuspension and ignition We now compare our new field observations to previous influential theory that predicts when a submarine turbidity current will autosuspend or ignite (Bagnold, 1962; Pantin, 1979; Parker, 1982; Parker et al., 1986). It is important to understand whether these unusually detailed field observations can provide a robust test of such theories.

357

#### 358 *4.4.1. Initial energy-balance theory*

Initial work (Bagnold, 1962; Pantin, 1979; Parker, 1982) formulated a theory for whether 359 turbidity currents autosuspend or ignite that is based on energy losses and gains by the flow. It 360 361 was assumed that movement of sediment down-slope results in loss of potential energy, whilst energy is expended by processes that keep sediment grains aloft. When energy gains equal or 362 363 exceed energy losses, the flow can carry all of the sediment it suspends. Then, if the flow can also 364 erode loose sediment from the bed, it ignites (Fig. 1). However, if no erodible material is 365 available, the flow autosuspends. Alternatively, if energy losses exceed energy gains, then some 366 of the suspended sediment will settle out, and the flow will eventually dissipate.

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Equation 1 and figure 6 result from this initial energy-balance theory (Bagnold, 1962; Pantin, 1979; Parker, 1982), as previously depicted by Sequeiros et al. (2009). Figure 6 predicts the threshold frontal velocity ( $u_h$ ) for ignition, as a function of sediment settling velocity ( $w_s$ ) and seafloor gradient ( $\beta$ ). The threshold constant for ignition to occur ( $\varepsilon$ ), varies between different authors. Bagnold (1962) and Parker (1982) assume that potential energy gain must at least equal or exceed energy losses ( $\epsilon \le 1$ ). In contrast, Pantin (1979) assumes that only a small fraction ( $\epsilon \le 0.01$ ) of potential energy gain will be available to keep sediment aloft, with most potential energy being dissipated in other ways.

Equation (1) 
$$\frac{w_s \cos\beta}{u_h \sin\beta} \le \varepsilon \begin{cases} \varepsilon = 0.01 & (Pantin, 1979) \\ \varepsilon = 1 & (Parker, 1982) \\ \varepsilon = \cos\beta & (Bagnold, 1962) \end{cases}$$

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As we use the flow front velocity  $(u_h)$ , we only consider whether ignition or autosuspension occurs near the flow front. As noted by past authors (e.g. Bagnold, 1962; Pantin, 1979; Parker, 1982; Sequeiros et al., 2009), Equation 1 is a necessary condition for ignition, but it is not a sufficient condition for ignition; indeed it is rather conservative (Parker et al., 1986). Suitable sediment must also be available for erosion and incorporation into the flow. This might not be the case, for example, if the flow was moving over hard bedrock.

383

384 Measurements from Monterey Canyon can be combined with Equation 1 to compare observed and predicted flow velocities associated with ignition (Fig. 6). We use a seabed gradient of  $2^{\circ}$ 385 386 (Fig. 1e) (Paull et al., 2018), and sediment traps on moorings for grainsize distributions for three separate turbidity currents. The sediment trap closest to the location of ignition in that flow is 387 388 used (Fig. 1c), together with the coarsest subsample from each flow deposit in that trap. These traps were initially suspended 10 m above the bed, but they were sometimes dragged closer to the 389 bed during the first few minutes of flow (Paull et al., 2018). The method of Ferguson and Church 390 391 (2004) is used to estimate settling velocities for individual grains, which assumes that flow is 392 dilute. Settling velocities could become hindered at higher sediment concentrations.

Figure 6 shows transit (average frontal) velocities needed for ignition for the grain sizes captured
by traps in the Monterey Canyon flows, for different values of ε that have been proposed
previously. There is reasonable agreement between our field observations with the approach of
both Parker (1982), and Bagnold (1962). Where flows ignited in Monterey Canyon, grain sizes
observed in sediment traps mainly lie within the field of ignition (Fig. 6). There is poorer
agreement with Pantin (1979), suggesting that potential energy losses do not need to be 100 times
greater than energy losses to keep sediment aloft, and thus for ignition to occur.

401

#### 402 4.4.2. Subsequent more complex turbulence energy-balance theory

The simple energy-balance approach summarized by equation 1 (Bagnold, 1962; Pantin, 1979; Parker, 1982) sets out a necessary condition for autosuspension or ignition. However, flows that fulfil equation 1 need not ignite, as other conditions are also important. For example, sediment exchange with the seabed will strongly influence flow density and thus velocity (Parker et al., 1986; Traer et al., 2012), whilst entrainment of surrounding water will cause momentum to be lost (Parker et al., 1986).

409

Parker et al. (1986) therefore subsequently developed a more advanced and complete theory. This
theory initially comprised three layer-averaged equations based on budgets of fluid (water) mass,
sediment mass and momentum within the flow (Parker et al., 1986). A fourth layer-averaged
equation was then based on budgets of turbulent kinetic energy within the flow, including
turbulence production at the upper and lower flow boundary, dissipation of turbulence due to
viscosity, and work done by turbulence against vertical density gradients (Parker et al., 1986).

This approach led to a more complex criterion for ignition (equation 16 of Parker et al. (1986)).
This criterion involves layer-averaged sediment concentration, flow velocity and thickness,
sediment settling velocity, bed shear velocity, and rates of sediment and water entrainment
(Parker et al., 1986). This more advanced but complex criterion for ignition implicitly assumes
that sediment is mainly supported by fluid turbulence. It would not apply to denser sediment
flows in which turbulence is strongly damped, and where other processes become important for
sediment support, such as support via grain-to-grain collisions, or excess pore pressure.

423

#### 424 **4.5.** Why past autosuspension and ignition theory is difficult to test

Although unprecedented in their detail, our field observations from Monterey Canyon provide a
rather weak test of the initial simpler energy-balance theory (Bagnold, 1962; Pantin, 1979;
Parker, 1982), and they are unable to test the more complex turbulent energy-balance (Parker et
al., 1986) theory, for three key reasons.

429

First, both types of theory involve a single sediment settling velocity, and thus require that a representative grain size is chosen. However, turbidity currents in Monterey Canyon contain a wide range of grain sizes (Fig. 6), as is often the case for turbidity currents elsewhere. Thus, there is an issue of which representative grain size to choose from this wide distribution (Fig. 6). There are also major issues related to measurement of grain size in the field via sediment traps, as traps only sample grain size at a single height, and traps may be less effective at capturing finer grains than coarser grains.

438 Second, in the case of theory based on turbulent kinetic energy budgets (Parker et al., 1986), we
439 lack sufficiently precise measurements of key parameters needed by this theory, most notably
440 layer-averaged sediment concentrations, but also rates of sediment and water entrainment.
441

442 Finally, and most importantly, some key assumption that underpin past theories may not hold. 443 For example, Parker's later theory based on turbulent kinetic energy budgets assumes that flow is dilute, such that turbulence is always the main support mechanism (Parker et al., 1986). Field 444 evidence suggests that some turbidity currents in Monterey Canyon are driven by dense near-bed 445 446 layers with high (> 10% by volume) sediment concentrations (Fig. 6) (Paull et al., 2018). These dense layers are needed to explain the fast ( $\geq 4 \text{ m/s}$ ) movement of very heavy (up to 800 kg) 447 448 objects for several kilometres (Paull et al., 2018). It is unlikely that entirely dilute flows could carry such heavy objects, at high velocities, for such distances; the heavy objects are instead 449 entombed in a dense near-bed layer (Paull et al., 2018). Turbulence is damped strongly in such 450 451 dense near-bed layers, and settling will be hindered (Winterwerp, 2006). Other sediment support 452 mechanisms become important, such as grain collisions or excess pore pressures that partly carry 453 the sediment load. The more advanced ignition theory (Parker et al., 1986) would thus be unable 454 to capture the behaviour of flows in Monterey Canyon with dense near-bed layers.

455

#### 456 **4.6.** New travelling wave model

We now outline a new conceptual model for how initially fast moving turbidity currents operate in confined settings, underlain by loose sand, based on our field observations. Following Paull et al. (2018), this model includes dense near-bed layers that drive the flow, in which turbulence is not the main support mechanism. The model thus better fits detailed field observations from Monterey Canyon. A new model is needed because past theory for ignition and autosuspension
(Parker et al., 1986) was not formulated to include dense near-bed layers. The new model differs
from past work (e.g. Paull et al., 2018), as it explains how flows that initially ignite may then
autosuspend, as they reach a uniform transit velocity.

465

We propose that during initial ignition, and the following near-equilibrium (autosuspension) 466 phase, a fast and dense near-bed layer exists at the flow front, which drives the overall event, 467 similar to Fig. 7 (Winterwerp, 2006). This dense near-bed layer near the flow front maintains an 468 approximately uniform frontal velocity, as erosion of the bed near its front, is balanced by 469 470 deposition at its rear (Fig. 7). Thus, although the dense layer is locally either erosive or depositional at a single location, erosion and deposition are balanced over the whole of the layer, 471 such that the dense layer velocity is near-uniform. This leads to autosuspension (Fig. 7). We 472 envisage that sediment concentrations in the dense layer (10-30%) are those attributed by 473 Winterwerp et al. (1992) to hyperconcentrated flow, which is capable of forming the crescentic 474 shaped bedforms seen along the floor of Monterey Canyon (Winterwerp et al., 1992; Paull et al., 475 476 2018). It has been suggested that liquefied flows of sand could only travel for short distances (Lowe, 1976) on steep slopes  $(>3^\circ)$  due to rapid dissipation of excess pore fluid pressures and 477 478 basal sedimentation. However, addition of small fractions of cohesive mud, as seen in Monterey Canyon (Maier et al., 2019), increase the time taken for excess pore pressure to dissipate by 479 orders of magnitude and hinders settling (Iverson et al., 2010), thus greatly increasing runout of 480 481 partly-liquefied flow. Sediment from the dense layer is shed backwards into a dilute and fully turbulent sediment cloud. This trailing cloud increases in length (stretches) as the dense flow 482 front runs ahead of the trailing body (Figs. 3 and 6) (Azpiroz-Zabala et al., 2017). 483

We term this new model the 'travelling wave model', and it is broadly comparable to behaviour 485 486 seen in laboratory experiments involving dense, dry granular avalanches (Supplementary fig. 6) (Pouliquen and Forterre, 2002; Mangeney et al., 2007). A key feature of these experiments is that 487 the dry avalanches that are fast enough can erode their underlying substrate, in their case loose 488 489 sand. These dry granular avalanche experiments show two types of behaviour (Pouliquen and Forterre, 2002; Mangeney et al., 2007). Slower moving avalanches dissipate, as they fail to erode 490 and entrain their substrate. However, sufficiently fast moving dry granular avalanches erode, and 491 492 form a travelling wave with near-uniform frontal transit velocities (Supplementary fig. 6) (Pouliquen and Forterre, 2002; Mangeney et al., 2007; Edwards and Gray, 2015). Erosion of sand 493 from near the front of the travelling wave is balanced by deposition from its rear (Fig. 7). The 494 avalanche thus contains a substantial fraction of locally eroded material. The transit velocity of 495 this travelling wave is strongly determined by the thickness of the frontal avalanche, as in the dry 496 granular experiments (Pouliquen and Forterre, 2002; Mangeney et al., 2007). Frontal thickness 497 determines the down-slope driving force near the front, at least for near-uniform gradients and 498 499 flow densities. The flow thickness in turn depends on the depth of eroded material, and thus on 500 rates of frontal erosion (Pouliquen and Forterre, 2002; Mangeney et al., 2007). Turbidity currents will differ in key regards from these dry granular avalanches that occur on far steeper (>  $30^{\circ}$ ) 501 gradients. For example, erosion of water-saturated canyon floor sediment, such as via abrupt 502 loading and liquefaction, may allow turbidity currents to erode on much lower ( $< 2^{\circ}$ ) gradients 503 than dry granular avalanches. Settling velocities will be much greater in air, and turbidity currents 504 505 can also comprise trailing dilute suspensions. However, we draw a first-order analogy with the 506 ability of faster moving dry granular avalanches that exceed a threshold and erode their substrate, whilst depositing from their rear, and thus maintain dense flow with near-uniform transit velocity. 507

509	This new travelling wave model also needs to account for crescent shaped bedforms that are
510	abundant along the floor of Monterey Canyon (Paull et al., 2018), and many other sandy
511	submarine canyons (Symons et al., 2016), which have been linked to instabilities (termed cyclic
512	steps) in supercritical flows (Hughes Clarke, 2016). Bedforms in Monterey Canyon have
513	amplitudes of 1 to 3 m, and wavelengths of 20 to 80 m (Paull et al. 2018). As discussed in more
514	detail by Paull et al. (2018), tracking of extremely heavy (800 kg) objects showed that they
515	experienced repeated vertical oscillations of 1-3 m, as they were carried down Monterey Canyon
516	at velocities of ~4 m/s. Bedforms were thus most likely continuously present, and must have been
517	at least partly formed by the dense travelling wave. This is consistent with field observations and
518	laboratory experiments showing that cyclic steps and up-slope migrating bedforms can form
519	beneath supercritical flows with very high (20-40% volume) sediment concentrations
520	(Winterwerp et al., 1990, 1992) as well as dilute supercritical flows (Kostic and Parker, 2006;
521	Covault et al., 2017).
522	Future work is now needed to test this new travelling wave model, such as via direct
523	measurements of sediment concentration in turbidity currents, or by determining the importance
524	of locally derived or far-travelled sediment in near-bed layers.
525	
526	5. Conclusions
527	Here we analyse the most detailed measurements yet from within seafloor turbidity currents,
528	showing how their transit and maximum measured internal velocities vary with distance.
529	

Overall, we observed that small (< 0.5-1 m/s) increases in average transit velocities are associated</li>
with large differences in subsequent runout (Fig. 8). Fractional increases in initial velocities may

lead to flows with near-uniform velocities associated with autosuspension, enabling much longer
runout. Flows with only slightly lower initial velocities die out in upper or mid-canyon. Patterns
of transit and internal velocities with distance thus diverge markedly (Fig. 8).

535

However, one flow in Monterey Canyon is an exception to this general pattern, as it selfaccelerated mid-canyon (Fig. 8, dotted green line). It is also the only flow that occurred during
less-stormy summer months. Erosion of a weak surficial-mud layer with underlying fine sand, is
likely to also favour self-acceleration. Turbidity current behaviour may therefore be highly
sensitive to both initial transit velocities and substrate character.

541

Our observations show that initial self-acceleration (ignition) can be followed by a phase of near-542 uniform transit velocities (autosuspension), at least for initially faster flow events (Fig. 8). 543 544 Previous models have proposed that autosuspension may follow on from ignition, as erodible bed material runs out. But this is not the case in Monterey Canyon, as loose sand is available along 545 the canyon floor. Instead, we propose that flows are driven by thin and dense, frontal, near-bed 546 layers (which we call a travelling wave; Fig. 7). Faster moving travelling waves can reach an 547 autosuspending state, as frontal erosion balances deposition from their rear, so that near-uniform 548 549 frontal flow thicknesses and thus velocities are maintained. These dense travelling waves shed a slower moving dilute sediment cloud, which lengthens as the flow runs out. But this dilute cloud 550 does not drive the flow, and changes in its sediment concentration are thus less important. This 551 552 travelling wave model itself needs further testing, including via direct measurements of near-bed sediment concentrations, but it is consistent with movement of very heavy objects at high 553 554 velocity near the flow front (Paull et al., 2018).

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566	
567	Data and materials availability
568	Data are available at <u>https://doi.org/10.1594/IEDA/324529</u> .
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Figure 1. Ignition, dissipation and autosuspension of turbidity currents. (A) Ignition is 720 721 caused by net sediment erosion that increases flow density, causing increased velocities. This positive feedback cannot continue indefinitely, as elevated sediment concentrations eventually 722 damp turbulence, shield the bed from erosion, or increase friction. (B) Dissipation is caused by 723 sediment deposition, which leads to spatial decreases in flow density, and thus velocity. This 724 negative feedback causes the flow to eventually die out. (C and D) Autosuspension comprises a 725 situation in which flow density remains constant, and flow velocities are constant spatially. (C) 726 Flow may be powerful enough to suspend all of the sediment it carries, but the substrate is too 727 728 hard to erode. Alternatively, localised areas of erosion and deposition may also balance each other out, leading to no net change in suspended sediment. (D) Sediment deposition may be 729 balanced by an equal amount of substrate erosion. Models for autosuspension in (C) and (D) 730 assume flow is dilute and fully turbulent. We subsequently present an alternative model for 731 autosuspension (Fig. 7), where flow is driven by a dense near-bed layer. 732



#### 735 Fig. 2. Location, runout distances and velocities of turbidity currents in Monterey Canyon.

(A) Bathymetry map of Monterey Canyon showing location of moorings in this study (MS1 to

737 MS7, SIN), and Navy Slump. (B) Timing and runout distance of turbidity currents in Monterey

738 Canyon between October 2015 and April 2017. Horizontal lines show 13 events registered by

ADCPs. The green and yellow boxes show the 6-month deployment periods. Locations of

moorings (MS1 to MS7, SIN) are indicated. The exact point where flows terminate between
 moorings is uncertain. (C) Changes in flow velocity with distance along Monterey Canyon's

thalweg. Solid dots and solid lines show frontal velocities between moorings. Open symbols and

dotted lines show maximum internal velocity measured at each mooring by an ADCP, including

for some flows that only reached the first mooring (solid squares). (**D**) Changes in thalweg

745 gradient. (E) Changes in axial channel width, defined by the width of mapped bedforms.



747 Distance (km)
748 Fig. 3. Velocities of turbidity currents in Monterey Canyon and properties of the thalweg.
749 (A) Changes in flow velocity with distance along Monterey Canyon's thalweg. Solid dots and
750 solid lines show frontal velocities between moorings. Open symbols and dotted lines show
751 maximum internal velocity measured at each mooring by an ADCP, including for some flows
752 that only reached the first mooring (solid squares). (B) Changes in thalweg gradient. (C) Changes
753 in axial channel width, defined by the width of mapped bedforms.





Fig. 4. Turbidity current structure at consecutive snap-shots in time, showing changes in 758 flow-length, internal velocity-structure, and flow-thickness. Flow velocities between 759 moorings are inferred, as are velocities in the lower 3-4 m of the flow (due to ADCP side-lobe 760 interference). (A) Long run-out flow, which is initially fast, based primarily on the January 15<sup>th</sup> 761 event. The MS1 mooring was dragged down-canyon during the January 15<sup>th</sup> event. Thus, ADCP-762 data from the February 3<sup>rd</sup> event are used for MS1 in T1 snapshot, and it is unknown if the 15<sup>th</sup> 763 January flow was present at MS1 during the T1+70 min snapshot. (B) Shorter runout flow that 764 was initially powerful, but then dissipated rapidly, based on November 24<sup>th</sup> event. This event 765 carried an 800 kg object at  $\ge 4$  m/s, for ~1 km in the upper canyon (Paull et al., 2018). (C) 766 Example of an initially-weak turbidity current on September 1<sup>st</sup>, which then accelerated markedly 767 768 in the mid-canyon, and dissipated rapidly between MS5 and MS7. This is the only event that occured during summer months (Fig. 2b). 769

770



Distance (km)

Fig. 5. Changes in frontal velocities of turbidity currents over distance. Variations in seabed 772 gradient and flow confinement are also shown. (A) Frontal velocities of flows in Monterey 773 Canyon. Figure 3 shows detailed changes in seabed gradient and channel floor width. (B) Frontal 774 velocities of flows confined within Gaoping Canyon, offshore Taiwan, based on cable 775 776 breaks (Gavey et al. 2017). Average seabed gradients are shown, but detailed surveys of canyon width are currently lacking. (C) Frontal velocities of the Grand Banks turbidity current in 1929, 777 778 offshore Newfoundland, based on cable breaks (Heezen and Ewing, 1952; Hughes Clarke, 1988; Piper et al., 1999). Distance is from the initial earthquake epicentre, although coincident cable 779 breaks occurred over a wider area. The initial part of this flow was confined by submarine fan-780 valleys, but was unconfined during its later stages, as it spread across a basin plain (Piper et al., 781 1999). Detailed data on the seafloor gradient over the entire length of the event are lacking, and 782 783 are based on Stevenson et al. (2018) and Piper and Hundert (2002). 784





Fig. 6. Comparison of field measurements in Monterey Canyon to past energy-balance 788 theory for autosuspension, following Sequeiros et al. (2009). It shows the threshold flow 789 790 velocity predicted by three past theories, for a given grain-size and seabed gradient, above which 791 flows carry all suspended sediment (i.e. autosuspend). If seabed sediment is available for erosion, the flow will also ignite. Blue lines show the different threshold constants ( $\varepsilon$  in Equation 1) used 792 793 by different authors, assuming a seabed gradient of 2°. Autosuspension occurs below the lines. Note that results for the threshold constant of Bagnold (1962) coincide with those of Parker 794 (1982) for the case of Monterey Canyon. Grain-size distributions for three events (November 795 24<sup>th</sup>, September, 1<sup>st</sup>, and January 15<sup>th</sup>) in Monterey Canyon, based on sediment traps located 10 m 796 797 above the bed. The grain-size distributions shown here are averages for each event in sediment traps from the upper canyon where flows are assumed to ignite (see Material and Methodology, 798 799 Supplementary Fig. 5 for more information). The coloured boxes show the  $10^{\text{th}}$  percentile (D<sub>10</sub>) and  $90^{\text{th}}$  percentile (D<sub>90</sub>) of the coarsest grain-size samples in traps from each event. 800

#### Travelling wave model: erosive, dense frontal layer with near uniform front speed



#### 801 802

**Fig. 7. New travelling wave model.** Travelling wave model for turbidity current behaviour in loose-sand submarine canyons, in which flows contain a fast and dense near-bed layer at their

front, as proposed by (Paull et al., 2018). Erosion at the front of this dense near-bed layer is

balanced by sediment deposition from its rear, leading to uniform transit velocity and

autosuspension. Sediment is shed backwards to form a trailing sediment cloud that is dilute and

808 fully turbulent, which lengthens over time.



812 Fig 8. Summarising model for turbidity current behaviour in submarine canyons underlain

by loose sand. Patterns of flow behaviour, based on frontal transit velocities that are simplified
from Fig. 3a. Small increases in transit velocity at the first mooring are associated with major
differences in subsequent flow velocities and runout distance, causing divergence in flow

behaviour (purple, dark blue and light blue lines). However, flows can sometimes self-accelerate
and ignite within the mid-canyon (green dotted line), due to changes in substrate strength and

818 erodibility. There is a threshold initial transit velocity (red line) above which flows can819 autosuspend (purple line).

820

822 '	Table	1
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Flow Threshold	≥1 m/s						≥2 m/s						≥3 m/s								
Mooring	MS 1	MS 2	MS	MS 4	MS	SI	MS 7	MS 1	MS	MS	MS ⊿	MS	SI	MS 7	MS 1	MS 2	MS	MS 4	MS	SI	MS 7
Distance	67	2 16	26	4	43	51	52	67	2 16	26	40	43	51	52	67	16	26	4	43	##	52
(km)	0.7	10	0	0	10	8	02	0.7	10	0	0		8	02	0.7		0		10	#	02
lon 15		07	1 1 1	100	212	11	00		0.5	50		11	27	22		0.5	20		25	0.5	
Jan-15		0/	141	102	213	2	69		9.5	59	23	41	31			0.0	30	0	20	0.5	0
Sep-01	20	3.5	73		22	45	0	1	0.5	7	0	11	0	0	0.5	0	0	0	3	0	0
Feb-03	48	74	73	67	65	0	0	28	17	26	0	3.5	0	0	16	15	2.5	0	0	0	0
Feb-18	34	26	70	0				15	12	16					7.5	8	1.5				
Jan-09	35	23	43					19	11	0					11	8	0				
Nov-24	33	15						12	3.5						9	0.5					
Jan-21	31							9.5							2		-				
Jan-20	25							7							2.5						
Dec-01	16							7							3						
Jan-23	9							0							0						
Jan-06	6.5							1							0						
Dec-11	2.5							0							0						
Jan-22		,		37	0				,		0	0	]			,		0	0		



- 825 duration of the flow at each mooring. The ADCP data was displayed using contour lines corresponding to each threshold, allowing for
- 826 determination of flow duration at every mooring. Left hand columns denote flow velocity threshold  $\geq$  1 m/s. Middle columns denote flow

- velocity threshold  $\geq$  2 m/s. The right-hand column denotes flow velocity threshold  $\geq$  3 m/s. Where no flow duration is given, there was no ADCP
- 828 measurement (January 15, MS1, and September 1, MS4). A duration of 0 min indicates the flow is no longer measured at the specified threshold
- 829 velocity at that mooring.

#### **Graphical Abstract:**



Summarising model for turbidity current behaviour in submarine canyons underlain by loose sand. Small increases in initial velocity cause major differences in subsequent flow velocities and runout distance, causing divergence in flow behaviour (purple, dark blue and light blue lines). However, flows can sometimes self-accelerate and ignite within the midcanyon (green dotted line), due to changes in substrate strength and erodibility. There is a threshold initial transit velocity (red line) above which turbidity currents can autosuspend (purple line).