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1 Pulse propagation in turbidity currents

2

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9

10 ABSTRACT

11 Submarine turbidity currents are a key mechanism in the transportation of clastic sediments
12 to deep seas. Such currents may initiate with a complex longitudinal flow structure comprising
13 flow pulses (e.g. by being sourced from retrogressive sea floor slope failures) or acquire such
14 structure during runout (e.g. following flow combination downstream of confluences). A key
15 question is how far along channel pathway complex flow structure is preserved within
16 turbidity currents as they run out and thus if flow initiation mechanism and proximity to
17 source may be inferred from the vertical structure of their deposits. To address this question,
18 physical modelling of saline flows has been conducted to investigate the dynamics of single-
19 pulsed vs. multi-pulsed density driven currents. The data suggest that under most
20 circumstances individual pulses within a multi-pulsed flow must merge. Therefore initiation
21 signatures will only be preserved in deposits upstream of the merging point, and may be
22 distorted approaching it; downstream of the merging point, all initiation signals will be lost.
23 This new understanding of merging phenomenon within multi-pulsed gravity currents
24 broadens our ability to interpret multi-pulsed turbidites.

25

26 **Keywords:** turbidity currents, multi-pulsed turbidity currents, seismo-turbidites, pulsed
27 turbidites, stacked turbidites, signal shredding.

28 1. INTRODUCTION

29 Gravity currents are driven by a density difference between two fluids, and are widespread in
30 both industrial scenarios and natural settings. Turbidity currents are a form of dilute
31 particulate gravity flow in which the flows move under the gravitational action upon dispersed
32 sediments suspended within the interstitial fluid (Middleton, 1993; Huppert, 1998; Kneller &
33 Buckee, 2000; Sequeiros, 2012). Turbidity currents in natural settings can range up to
34 hundreds of meter in thickness (Piper *et al.*, 1988; Sumner & Paull, 2014) with durations that
35 may extend up to hours or days (Piper *et al.*, 1999; Xu *et al.*, 2004; Mikada *et al.*, 2006); they
36 are a principal mechanism by which sediment is transported from continents to deep seas
37 (e.g. Simpson, 1982; Talling *et al.*, 2015). Turbidity currents can be initiated by submarine
38 slope failures (triggered by earthquakes or other mechanisms) or by direct hyperpycnal
39 underflow into the oceans; they commonly flow through submarine channels into the deep
40 oceans (Mulder & Alexander, 2001; Best, *et al.*, 2005; Piper & Normark, 2009).

41

42 Sediments deposited by turbidity currents – turbidites - commonly exhibit
43 continuously upward fining of mean grain size (Fig. 1). This is referred to as “normal grading”
44 (Bouma, 1962; Lowe, 1982; Gutiérrez-Pastor *et al.*, 2013). However, it is not uncommon for
45 turbidites to show more complex grading profiles, such as inverse grading (e.g. Kneller and
46 McCaffrey, 2003; Mulder *et al.*, 2003). On the basis that the grain size at any particular level
47 in a deposit relates to the instantaneous basal shear stresses, normal grading suggests
48 deposition from a waning flow, whereas, inversely graded (upward coarsening) deposits
49 suggest deposition from waxing flow (Kneller & Branney, 1995; Kneller & McCaffrey, 2003;
50 Mulder *et al.*, 2003; Amy *et al.*, 2005; Basilici *et al.*, 2012, cf. Hand, 1997). A more complex
51 exception from normal grading patterns is seen when repeated intervals of coarsening are
52 seen superimposed upon an overall normally-grading profile. Beds exhibiting this pattern are
53 here described as a “pulsed” or “multi-pulsed” turbidites, as the implication is that pulses of
54 increased velocity occurred in the overpassing flow at the point of deposition. Pulsed
55 turbidites can be differentiated from “stacked” turbidites which, although superficially
56 similar, represent the closely vertically juxtaposed deposits of two or more individual turbidity
57 currents; in practice, distinguishing the two can be challenging where later flows erode into
58 the deposits of earlier flows to produce deposit amalgamation and intervening fine grained

59 material is absent. When submarine turbidites show deviations from a continuous normal
60 grading, a variety of mechanisms can be invoked to explain pulsed flow generation, for
61 example discrete episodes of retrogressive slumping (Piper *et al.*, 1999; Canals *et al.*, 2004;
62 Bull *et al.*, 2009), variations in ground shaking in currents initiated by single seismic events
63 (Goldfinger *et al.*, 2012), variations in the flood hydrograph for hyperpycnally generated flows
64 (Mulder & Alexander, 2001) and flow combination along the pathway of channel confluences
65 (Nakajima & Kanai, 2000; Ismail, *et al.*, 2016). In addition flow reflection in confined settings
66 has also been invoked to cause pulsing (e.g. Haughton, 1994). Research on how these
67 mechanisms might be distinguished in the depositional record of pulsing flows is less
68 extensive (see examples in Goldfinger *et al.*, 2012). A key consideration in this regard is how
69 long non-monotonic variations in mean flow velocity along the flow may persist from source,
70 and thus potentially be indicative of the flow generation mechanism; a related consideration
71 is whether the degree to which a deposit approaches a normal grading profile may be an
72 indirect indicator of distance from source.

73 Here, saline flow experiments are reported with the aim of informing understanding
74 of the dynamics and evolution of pulsed turbidity currents, and exploring the possible
75 implications for the interpretation of vertical depositional grading profiles. A principal goal is
76 to review and extend the inferences regarding flow behaviour and proximity to source that
77 can reasonably be made in natural turbidites. This contribution: i) presents novel
78 experimental data that detail the variation of multi-pulsed flow dynamics; ii) assesses how
79 flow dynamics may be interpreted from turbidite grading structure, and iii) reviews two case
80 studies in the which the interpretational template of turbidites with complex grading profiles
81 is reviewed and broadened.

82 **2. METHODOLOGY**

83 **2.1. Experimental set-up and research methodology**

84 The methodology of generating gravity currents in lock exchange flumes has been widely
85 applied by various authors (e.g. Middleton, 1966; Holyer & Huppert, 1980; Britter & Simpson,
86 1981; Lowe *et al.*, 2002; Gladstone *et al.*, 2004). In the work described here, lock exchange
87 experiments of saline flows were conducted in order to gain an understanding of the internal
88 dynamical structure of turbidity currents. Although they do not take into account the effects

89 of particle transport, as occurs in natural turbidity currents, saline flows are a well-established
90 proxy for studying such flows (e.g. Kneller and Buckee, 2000; Islam and Imran, 2010; Hogg *et*
91 *al.*, 2016). Similarly, turbulent laboratory-scale flows are thought to deliver a good
92 representation of the dynamics of flow at natural scale (e.g. Paola *et al.*, 2009). Figure 2 shows
93 the experimental set-up, in which a 5 m long Perspex flume with multiple lock-exchange gates
94 was used, incorporating overspill boxes at both ends to reduce the effect of waves caused by
95 the removal of the lock gates. Two 12.5 cm-long lock boxes were set up in series at one end
96 to enable the generation of multi-pulsed flows, using saline fluid with 5% density excess (1050
97 kgm^{-3}) as a proxy for turbidity currents. Using a pneumatic lock-gate driver, the upstroke
98 speed of each lock gate was set at 1.0 ms^{-1} so that any resulting turbulence was minimized,
99 without being so slow that a partially-withdrawn lock gate affected the counter flow of fluid
100 into the lock. The release time delay of the second gate could be adjusted to within $1/10 \text{ s}$ of
101 the first release; here it was set to 4 s so that the interaction between pulses in a bi-pulsed
102 flow occurred within the length of the flume. To model single-pulsed flows, the delay was set
103 to zero. The dense saline fluid was prepared in a 180 l mixer, and monitored to ensure
104 consistent density. It was pumped slowly into the lock boxes via an intake valve on the bottom
105 of each lock box, displacing fresh water above whilst preserving a sharp upper boundary. Each
106 lock box was filled to a depth of 0.05 m with dense fluid dyed yellow in the first box and blue
107 in the second to enhance flow visualization and front position tracking. The total lock box
108 depth equalled the 0.25 m depth of the external ambient. The 1:5 depth ratio maintains fully
109 turbulent, subcritical flow (Reynolds numbers were c. 2,000 and Froude numbers less than 1)
110 while allowing suitable depth scaling approximating to real-world submarine flow, where flow
111 to ambient depth ratios are 1:8 or greater (Piper *et al.*, 1988; Xu *et al.*, 2004).

112

113 Five HD interlinked cameras were deployed to capture a wide range of view of the
114 flume. The cameras were carefully aligned so as to prevent image distortions and stitching
115 artefacts. VirtualDub and Avisynth were used to stitch five linked video tracks together, based
116 on an audio time cue; camera synchronization was within 1 frame (0.042 s). The alignment of
117 the five cameras was checked using gridlines on the bottom of the flume (Fig. 3). The method
118 of profiling Acoustic Doppler Velocimetry (ADV) was used to measure spatio-temporal
119 variation of horizontal streamwise velocities (Craig *et al.*, 2011; MacVicar *et al.*, 2014; Brand

120 *et al.*, 2016). This methodology offers velocity profile measurements at high frequencies and
121 with high resolution. The ADV probe head was positioned 7.1 cm above the bed of the flume
122 at 13 different locations along the flume (Fig. 2), capturing a measurement of 30 mm flow
123 depth at each position. Both the dense fluid and the ambient were seeded with neutrally-
124 buoyant particles of 10 μm diameter to generate a consistent acoustic reflection. Spatio-
125 temporal depth-averaged velocity profiles were constructed for both single and multi-pulsed
126 flows using the following equation:

$$127 \quad \bar{u} = \frac{\int_0^h v \, dz}{h}$$

128 where v is the instantaneous velocity of the flow and $h = 0.03 \text{ m}$.

129 **2.2. Dynamics of density currents**

130 The dynamics of lock-gate release density currents can usefully be associated with the
131 slumping, inertial and viscous flow regimes of flow evolution, varying in each due to the
132 changing relative significance of buoyancy, inertial and viscous forces (Huppert & Simpson,
133 1980; Huppert, 1982; Rottman & Simpson, 1983; Bonnecaze *et al.*, 1993; Kneller *et al.*, 1999;
134 Amy *et al.*, 2005; Di Federico *et al.*, 2006; Huppert, 2006; Sher & Woods, 2015). The slumping
135 phase can extend up to 10 lock lengths from the initiation point; during this phase the gravity
136 current is driven mainly by buoyancy forces resulting from the density difference between
137 the dense fluid and the ambient. The buoyancy force of the flow is balanced by frictional
138 forces, principally caused by the return flow of ambient fluid balancing the slumping of dense
139 fluid out of the lock box; the flow travels with nearly constant velocity in the slumping phase.
140 During the inertial phase, inertial effects become important; this regime is characterized by
141 flow deceleration. Once the flow becomes sufficiently shallow, frictional forces exceed
142 buoyancy and inertial forces, and the flow enters the viscous phase, in which it continues to
143 decelerate.

144

145 **3. RESULTS**

146 Below, the results from the single- then multi-pulsed flows are described in sequence,
147 considering firstly the flow visualization data and then the flow velocity data.

148

149 3.1 Single-pulsed flow

150 To distinguish the frontal and rearward components of the single-pulsed flow, the denser
151 than ambient fluid in the front lock box was dyed yellow, and that in the rear blue, as shown
152 in Fig. 3A. As noted above, a zero second delay time between two lock gates enabled the
153 instantaneous trigger of the gates and the generation of a single release of the dense fluid.
154 Following the release, the dense fluid in the lock boxes collapsed, forming a negatively
155 buoyant density driven flow that propagated along the bottom of the flume. As the current
156 advanced along the flume, the blue portion of dense fluid comprising the rear 50% of the flow
157 at initiation was advected towards the front of the current (Fig. 3A, $t=2-4$ s; cf. Sher & Woods,
158 2015). The advection formed a visible intrusion around half of the flow depth, similar to
159 advection in Poiseuille flow (Lowe *et al.*, 2002; Sher & Woods, 2015). The dyed components
160 of the flow are inferred to have progressively mixed, changing the flow colour from
161 yellow/blue to green. In addition, the variation in the degree of mixing between the dense
162 fluid and the ambient is qualitatively indicated by the change in relative colour intensity of
163 the green fluid (Fig. 3A, $t=2-18$ s). This change is especially pronounced at the flow head,
164 where turbulent mixing processes are largest, due to shear-driven generation of Kelvin-
165 Helmholtz billows (Britter & Simpson, 1978; Johnson & Hogg, 2013).

166

167 The tracking of flow front positions using video data and the collection of velocity time
168 series using fixed instrumentation at different downstream locations permit velocity profiles
169 of both single- and multi-pulsed flows to be detailed (Figs. 4, 5 and 6). By tracking the positions
170 of the front (yellow) and rear (blue) components of the single-pulsed flow, two dynamical
171 flow regimes can be identified. In the initial slumping phase, the flow advanced at a nearly
172 constant velocity of c. 0.082 ms^{-1} for 1.25 m (c. 5 lock lengths). During the succeeding inertial
173 phase, the flow decelerated from 0.082 ms^{-1} to 0.008 ms^{-1} s over 2 m. The viscous phase of
174 the flow was not observed in the length of the flume covered by the cameras. The rearward
175 portion of the single-pulsed flow was advected forwards within the flow at a nearly constant
176 velocity of 0.1 ms^{-1} , i.e., 25% faster than the flow head, reaching the flow front during the
177 slumping phase some 0.8 m from source (Fig. 4A). The single-pulsed flow (Fig. 5A) displayed
178 the rapidly waxing and progressively waning velocity structure which is usually observed in
179 lock-gate release experiments (e.g. Simpson, 1982; Kneller *et al.*, 1999). The velocity

180 maximum was located at c. 25% of the local flow depth, as commonly seen in laboratory
181 experiments, field data and theoretical models (e.g. Kneller & Buckee, 2000; Talling *et al.*,
182 2015). The magnitude of flow velocity was observed to decrease with increasing time and
183 distance from source, as indicated by the change in colour intensity in Fig. 5A. The depth of
184 the flow may be estimated by using the vertical velocity profile to establish the height of the
185 zero velocity contour that separates downstream from upstream (return) flow (Dorrell *et al.*,
186 2016); e.g. in Fig. 5A at 0.365m downstream position and 2.5s, $h=0.015\text{m}$. The spatio-
187 temporal variation of depth-averaged velocity for single-pulsed flow is shown in Fig. 6A in
188 which the boundary of the black region indicates the arrival of the flow in time and space. The
189 plot shows a model of standard flow evolution in which the head velocity, indicated by the
190 yellow to orange regions behind the black edge, is constantly high within slumping phase (up
191 to the distance of about 1.4 m in Fig. 6A) and then decreases with increasing time and
192 distance.

193

194 **3.2. Multi-pulsed flow**

195 Initially, a single flow pulse dyed yellow was released from the front lock box and propagated
196 along the flume in the form of a negatively-buoyant density current (Fig. 3B, $t=2\text{ s}$). The second
197 pulse was triggered 4 s after the first one, at which time the fluid comprising the initial release
198 had collapsed to approximately one fourth of its initial depth in the front lock box (Fig. 3B, $t=4$
199 s). The second pulse was quickly advected towards the front of the flow, in the form of a
200 visible intrusion with sharp boundaries, at approximately half of the height of the first pulse
201 (Fig. 3B, inset $t=11\text{ s}$). The colour change from yellow and blue to green reflects the
202 progressive mixing between the two pulses (Fig 3B, $t=11-18\text{ s}$). Eventually, the two pulses
203 merged at a distance 1.4 m from source and the whole flow evolved in a manner similar to
204 that of a single-pulsed flow during its inertial phase (Figs. 3 and 4). Kelvin-Helmholtz billows
205 were generated on the back of the flow head, enhancing turbulent mixing in the flow and
206 between the dense and ambient fluid (Britter & Simpson, 1978; Johnson & Hogg, 2013). Thus
207 the colour shift at the flow head, as indicated by the variation in colour intensity of the green
208 (mixed) fluid, was intensified (Fig. 3B, $t=2-18\text{ s}$).

209 Front position tracking and the collection of velocity time series enabled velocity profiles of
210 the multi-pulsed flows to be detailed (Figs. 5 and 6). The first pulse entered its slumping phase

211 at initiation, and had travelled at a nearly constant velocity of 0.079 ms^{-1} for 0.65 m,
212 (approximately five 12.5 cm lock lengths) before the second pulse was released. The second
213 pulse was released 4 s after the first (Figs. 4B and 5B) and progressively intruded into it. The
214 combined flow accelerated at the point when the intrusion reached the flow head (Fig. 4B,
215 inset) advancing at a nearly constant velocity of c. 0.074 ms^{-1} for 0.25 m from the point of
216 merging. Thus, the slumping phase of the multi-pulsed flow lasted over 1.40 m (approximately
217 six 25.0 cm lock lengths). The slumping phase ended at 1.65 m from source. The velocity of
218 the second pulse averaged nearly 0.110 ms^{-1} , which is approximately 35% greater than the
219 initial head velocity of the first pulse. The inertial phase of the merged multi-pulsed flow was
220 characterized by a reduction in velocity to 0.012 ms^{-1} over a distance of about 1.85 m between
221 1.65 m to 3.5 m from source (Fig. 4B). As with the single-pulsed flow experiments, the viscous
222 phase of the multi-pulsed flow was not captured within the camera range of these
223 experiments. The multi-pulsed flow displayed a more complex velocity structure than the
224 generic waxing-waning velocity profile observed in lock-release single-pulsed gravity currents
225 (Fig. 5B). Two separate pulses of relatively high velocity ($>0.1 \text{ ms}^{-1}$) were distinctly observed
226 proximally to source (Fig. 5B, 0.365 m). The time separation between two pulses decreased
227 as the second pulse was progressively advected towards the front of the first pulse (e.g. Fig.
228 5B, 0.365 m, 0.675 m and 0.865 m). At the point of merging, the two pulses tended to have
229 similar velocities. Beyond the point of merging, the merged flow exhibited essentially the
230 same waxing-waning velocity structure as observed in the single-pulsed flow experiments
231 (Fig. 5A-B, 1.265 m, 1.665 m). The velocity maximum was also located at about 20% of the
232 flow depth, as observed in the single-pulsed flow experiments. In order to visualize the spatio-
233 temporal variation in the velocity profile of the multi-pulsed flow, a contour plot showing the
234 depth-averaged velocity of the flow was constructed (Fig. 6B). The depth-averaged velocity
235 of the first pulse was relatively high proximal to source (0.1 ms^{-1}). The high intensity region
236 surrounding the dotted line on Fig. 6B indicates the signal of the advection of the second pulse
237 within the first pulse. The initial relative timing of this signal was distorted by being
238 progressively reduced towards the point of merging. Beyond this point, the signal of the
239 second pulse intrusion in the velocity profile was completely lost (i.e., “shredded”, *sensu*
240 Jerolmack & Paola, 2010; Figs. 5B and 6B).

241

242 **3.3. Single-pulsed vs. multi-pulsed flows**

243 Multi-pulsed flow evolution is characterized by interaction of the separate pulses which
244 eventually merge at some distance from source; such flows exhibit a pulsing character up to
245 the point of merging. This pulsing characteristic is not seen in single-pulsed density currents.
246 Figure 7A shows raw (unfiltered) data detailing the temporal variation of depth-averaged
247 velocities of the single- vs. multi-pulsed flows, shown proximally to source, at the point of
248 merging and distally from source. The surface waves set up at flow initiation were not
249 completely removed by the overspill boxes, and resulted in a fluctuation in the raw data; the
250 magnitudes of the fluctuations are relatively small compared to the front velocity of the flows,
251 and are not thought to have significantly influenced the flow dynamics. To more clearly assess
252 the flow dynamics, the raw velocity data are filtered and replotted in Fig. 7B. Before the point
253 of merging, the depth averaged velocity profile of single-pulsed flows exhibited a standard
254 waxing-waning velocity structure whereas the profile of multi-pulsed flows has two
255 pronounced pulses (0-7 s at 0.365 m Fig. 7B). The time delay measured between the two
256 velocity pulses depends on initial lag time at initiation, and also upon the point of
257 measurement. Up to the point of merging, the time separation between the two pulses in
258 multi-pulsed flows progressively decreased. For the multi-pulsed flow, after the peak of the
259 second pulse passed the position of profiling, the velocity magnitude of the flow became
260 comparable to that of a single-pulsed flow comprising the same initial dense fluid. In distal
261 regions, both single- and multi-pulsed flows showed similar velocity structures to the normal
262 waxing-waning velocity profile (Fig. 7B).

263

264 **4. DISCUSSION**

265 **4.1. Multi-pulsed turbidity current propagation**

266 Turbidity currents commonly develop vertical density stratification during runout, due to the
267 entrainment of ambient fluid (Britter & Simpson, 1978; Hallworth *et al.*, 1996), particle
268 settlement (Baas *et al.*, 2005) and also due to recirculation of fluid from the body into the
269 head, where it is mixed and ejected backwards (Lowe *et al.*, 2002; Sher & Woods, 2015;
270 Hughes, 2016). It is inferred that both the single-pulsed density currents and the first pulse of
271 multi-pulsed flows developed vertical density stratification; the change within the first pulse

272 from an initial vertically homogeneous density profile to a stratified one can be seen from the
273 development of a green to yellow vertical transition in the single-pulsed flow (Fig. 3A) and in
274 the upward-lightening yellow colour intensity in the multi-pulsed flow (Fig. 3B). Consequently
275 the second pulse intruded into the first at a neutrally buoyant level and was advected within
276 it.

277 In gravity currents the velocity maximum is usually at approximately one quarter of
278 the flow depth, with the maximum velocity being greater than the speed of the flow front
279 (Figs. 3 and 5, Kneller *et al.*, 1999; Lowe *et al.*, 2002; Sher & Woods, 2015). Consequently,
280 material from the back of the flow is advected towards the head (e.g. Sher & Woods, 2015);
281 Gladstone *et al.*, (2004) noted in this regard that density stratification in the pre-release fluid
282 leads to preferential advection of lighter fluid towards the flow front. However, previous
283 studies have focused on the case in which flow properties vary monotonically behind the
284 head, and not considered the case in which the longitudinal velocity structure is
285 heterogeneous, i.e., when multiple pulses are initiated separately in time but eventually
286 merge distally from source, resulting in cyclic waxing-waning velocity structure in the flow
287 dynamics.

288 Here advection is visualized by separating both single- and multi-pulsed flows into
289 primary and secondary components, corresponding to the front and back of the flow at
290 initiation (Fig. 3). In the single-pulsed flow, the second component essentially moved with the
291 fluid immediately in front, and quicker than the current head velocity. In the multi-pulse
292 flows, the internal fluid velocity of the second pulse exceeded both that of the fluid pulse
293 immediately preceding it and of the current head velocity (Fig. 6 and section 4.2), resulting in
294 the forward advection of the second pulse being accelerated compared to that of the second
295 flow component in the single-pulsed flows. The tracked advection rates of the second pulse
296 in multi-pulsed flows were 10% larger than the internal flow front visualized in the single-
297 pulsed flows, i.e., c 0.11 ms^{-1} vs. 0.10 ms^{-1} (Fig. 4). The increase in internal advection may in
298 part be attributed to the additional momentum generated by the second lock-gate release.
299 Effectively, in multi-pulse system the second flow component is restrained by the second lock
300 gate, against gravity, for longer than in the single-pulse experiments. Thus, the delay between
301 two releases creates a greater pressure difference in the multi-pulse system than that in the
302 single-pulse system, due to the difference in the height of dense fluid in the two lock boxes.

303 By the time of the second lock gate release, the enhanced pressure gradient results in the
304 formation of an internal wave and thus an increase in internal advection rates in the multi-
305 pulse system.

306 Furthermore, in the multi-pulse system, the second pulse is released into the stratified
307 remnant of the primary pulse. Stratification of the primary pulse is driven by entrainment of
308 ambient fluid into the primary pulse after it has been released. The secondary pulse therefore
309 forms and propagates on a neutrally buoyant level, in a similar fashion to intrusions in
310 stratified quiescent fluids (Britter & Simpson, 1981; de Rooij *et al.*, 1999; Bolster *et al.*, 2008)
311 but here modulated by the background velocity field of the primary pulse. As mixing induced
312 stratification gradually decreases density of the primary pulse towards the density of the
313 ambient, and as the secondary pulse is denser than the ambient, the secondary pulse will be
314 confined within the primary pulse. If the secondary pulse is denser than the primary pulse the
315 intrusion will occur along the lower boundary of the flow. A consequence is that the second
316 pulse will experience reduced drag as its interaction with the solid lower and upper flow-
317 ambient fluid boundary is limited, i.e. lower and upper interface shear-stress (Härtel *et al.*,
318 2000) is reduced in comparison to single, or the primary component of multi-pulse flows (Fig.
319 8).

320 Given that internal fluid velocity in the body of a gravity current is always greater than
321 the head velocity (Kneller *et al.*, 1999; Lowe *et al.*, 2002; Sher & Woods, 2015), once a
322 following pulse has begun to interact with the velocity field of the first pulse, the second pulse
323 must eventually be advected towards the flow front. Therefore, it is concluded that the
324 intrusion of the second pulse and the merging of two pulses seen in the experiments is an
325 inevitable consequence of the interaction between pulses within dilute multi-pulsed density
326 flows.

327

328 **4.2. Conceptual models of deposition from multi-pulsed flows**

329 Since the flow dynamics of multi-pulsed flows vary along the flow pathway differently to those
330 of single-pulsed flows, the spatial evolution of their deposits is expected to be distinguishable.
331 Given that upward-fining and upward-coarsening grading patterns suggest deposition from

332 waning and waxing turbidity currents, respectively (Kneller & Branney, 1995; Hand, 1997;
333 Mulder *et al.*, 2003; Amy *et al.*, 2005; Basilici *et al.*, 2012), the waxing-waning phenomenon
334 within multi-pulsed flows should lead to the deposition of inverse graded intervals
335 corresponding the passage of a pulse (assuming the flow remains depositional and that an
336 appropriate range of grain sizes is available for transport). In addition, the grading patterns of
337 multi-pulse turbidites likely vary from proximal to distal regions, due to the progressive
338 advection of pulses towards the flow front with increasing run-out distance. This advection
339 should result in a progressive reduction in the time between pulses, decreasing to zero at the
340 point of merging with the flow head; where multiple pulses are present, some may
341 amalgamate before this point. Hence, in any associated turbidite deposit, an original pulsing
342 signal might be relatively accurately preserved proximally, such that the relative spacing
343 between inverse to normal grading cycles is representative of the timing differences between
344 pulses at initiation. The signal might then be progressively distorted up to the point of
345 merging, expressed in reductions in the relative vertical spacing of inverse to normal grading
346 cycles and also in a reduction in the number of such cycles present. The signal will eventually
347 be lost once all pulse components of the flow have completely merged. It should be noted
348 that the relative spacing between cycles will also be dependent on the sedimentation rate.

349 Figure 9 shows the likely links between a range of turbidity current types, as defined
350 by their longitudinal velocity structures, and their associated turbidite deposits. The deposits
351 are based upon usage in, e.g. Bouma (1962), Lowe (1982) and Gutiérrez-Pastor *et al.*, (2013)
352 and references therein. Thus single turbidites with normal grading are deposited by single-
353 pulsed turbidity currents (Fig. 9A). Stacked turbidites represent the closed vertically
354 juxtaposed deposits of two or more such flows (Fig. 9B); the close spacing is taken to imply
355 short inter-flow time durations. Amalgamated turbidites (Fig. 9C) are compound deposits of
356 two (or more) flows in which the later flow eroded into the deposits of the earlier flows.
357 Pulsed turbidites (Fig. 9D) are the deposits of multi-pulsed flows whose individual pulses have
358 interacted; depending on the cause of the pulsing, during early pulse interaction (e.g. Fig. 9D-
359 i) each deposition interval may be similar to a single turbidite, but without any evidence that
360 might indicate a period of flow inactivity between each one (e.g. turbidite mud or
361 hemipelagite). When the pulses have significantly interacted (e.g. Fig. 9D-ii) the time
362 separation between them, and thus the vertical separation of cycles in the deposit, will be

363 reduced. Note: the terms pulsed and stacked turbidites are used here regardless of the
364 originating mechanism of the pulses or whether pulses have distinct mineralogical character.

365 The initial delay times between different pulses in a multi-pulsed flow depend on the flow
366 generation mechanisms. For a flow initiated by a series of retrogressive submarine landslides,
367 each pulse can be linked to a discrete slumping episode and thus the delay times between
368 individual pulses are controlled by the timing between successive failures. This timing may
369 relate to the natural rate of slope instability propagation, but for a flow initiated by a single
370 large multi-pulsed earthquake or by closely spaced initial shocks and aftershocks (e.g.
371 Goldfinger *et al.*, 2012), the delay times may relate to the spacing between different
372 components of the seismic shock. When a multi-pulsed flow is formed by the combination at
373 channel confluences of different single-pulsed turbidity flows, which were initially triggered
374 synchronously in different channel heads, the delay time between pulses depends on the
375 arrival time differences of the individual flows at the confluence (which depend in turn on
376 channel lengths and intra channel flow velocities). The implications for deposit interpretation
377 for each of these formation mechanisms are considered below.

378 The depositional structure of flows initiated by retrogressive slope failures (whether
379 seismically generated or not) is shown in Fig. 10A. If there is no initial interaction between the
380 two single-pulsed flows, stacked turbidites could be expected to form proximally. If the flows
381 start to interact, the second flow would behave as a second pulse in a combined flow, and
382 would thus be advected progressively towards the front of that flow. The vertical depositional
383 structure would transition along the flow pathway from having a stacked to multi-pulsed
384 character, finally becoming uni-pulsed (or single-pulsed) after the point of pulse merging.
385 When initially distinct flows combine at confluences, the longitudinal variation in the vertical
386 grading structure of associated turbidites is expected to be similar to that postulated in Fig.
387 10A, but with an additional pulsing character acquired at the point of combination. In Fig. 10B
388 a case is shown in which flows are triggered synchronously in each of three channels C1, C2
389 and C3 but take different times to reach their first downstream confluence. This 3D model is
390 extrapolated from the 2D experimental configuration. The actual deposit character will vary
391 depending on the magnitude of each pulse and the nature of the setting. For example, a bi-
392 pulsed flow is shown forming at the C1-C2 confluence, and persisting to from C1-C2 to C3
393 confluence, where it merges with the flow in C3 to make a tri-pulsed flow that eventually

394 evolves into a uni-pulsed flow. However, had the constituent pulses of the flow formed at the
395 C1-C2 confluence already merged before the C1-C2 to C3 confluence, uni-pulsed flows in
396 channels C1-C2 and C3 would have combined to make a bi-pulsed flow, depositing a bi-pulsed
397 turbidite immediately downstream, and a uni-pulsed turbidite more distally. If the delay times
398 between flows were sufficiently long to prevent their interaction single turbidites would be
399 deposited in each of channels C1, C2 and C3, two stacked turbidites would be deposited
400 downstream of the C1-C2 confluence and three downstream of the C1-C2 to C3 confluence.
401 In complex natural settings, multi-pulsed turbidity currents can be generated by both
402 retrogressive slumping, with pulse timing either dictated by the timing of seismic shaking or
403 by unforced slope failure processes, and by flow combination at confluences of flows that
404 may or may not have a primary pulsed character.

405 It should be noted that the depositional models proposed in Fig. 10 disregard the
406 effects of flow bypassing (e.g. Stevenson *et al.*, 2013; Talling, 2013) or erosion and of local
407 topography features (Eggenhuisen *et al.*, 2010). Were bypassing or erosion to occur during
408 flow run-out, some parts of the vertical grading profiles described in the figure might be
409 partially or fully absent, with concomitant increases in deposit thicknesses further
410 downstream.

411

412 **4.3. Seismo-turbidites**

413 Earthquake-triggered turbidites are commonly deposited along large, active tectonic margins
414 such as Cascadia and Sumatra (Goldfiner *et al.*, 2007; St-Onge *et al.*, 2012). The deposits of
415 flows generated in this way are called “seismo-turbidites” (*sensu* Shiki *et al.*, 2000, and
416 references therein). Here the potential application of the conceptual models described above
417 is investigated, both to refine models of flow evolution and to suggest new interpretational
418 options. Sumner *et al.* (2013) document drop-core – derived records of Holocene turbidites
419 deposited on the southwest Sumatra margin, and consider whether they were seismically
420 triggered. Of interest here are turbidites with complex grading patterns, such as those
421 recovered from the updip 4MC and downdip 2MC locations (Fig. 11A). At the 4MC location a
422 succession of three turbidite units without intervening hemiplegic sediments have a
423 deposition motif that could be interpreted either as stacked turbidites (separate events, Fig.

424 9B), the interpretation favoured by Sumner *et al.* (2013), or as a tri-pulsed turbidite (one
425 event, Fig. 9D), deposited by a single, pulsed, seismically-generated turbidity current. The
426 sequence of deposits at 2MC appears to comprise one thick basal turbidite and two much
427 thinner overlying turbidites (Sumner *et al.*, 2013); the overall upward-fining grading profile of
428 the basal 2MC turbidite suggests that it is the deposit of a single-pulse flow (e.g. Fig. 10A).
429 Sumner *et al.*, (2013) did not correlate the 2MC deposit to other turbidites found locally in
430 the system such as those at 4MC. Although this interpretation may correctly reflect that the
431 4MC and 2MC locations did not lie on the same fairway, an alternative explanation now
432 permitted by the work detailed here is that the 4MC tri-pulsed turbidite and the uni-pulsed
433 2MC turbidite could represent the deposits of a single flow that was tri-pulsed at 4MC but
434 evolved via pulse merging to be uni-pulsed at 2MC (Fig. 10). In this interpretation, the pattern
435 of ground shaking that initiated flow might be distinguishable in the deposits at 4MC, but
436 have been shredded at 2MC.

437 Cascadia channel is the channel that extends downstream from the confluence of the
438 Juan de Fuca and Willapa channels (Fig. 11B; Goldfinger *et al.*, 2016). Core-based studies of
439 Holocene sediments suggest that great earthquake shocks/aftershocks commonly result in
440 the deposition of multi-pulsed turbidites in the Cascadia Basin (Goldfinger *et al.*, 2007;
441 Gutiérrez-Pastor *et al.*, 2013). For example, where the same number of turbidites are found
442 in each of the tributary channels and downstream of confluence of a linked channel system,
443 it can be inferred that seismic events synchronously triggered turbidity currents in each of the
444 tributaries, such that turbidity currents combined at confluences (Goldfinger *et al.*, 2012).
445 Thus, should the number of coarse-grained sediment intervals within a correlated bed
446 increase downstream of a confluence, the extra pulses were likely generated by a flow
447 combination mechanism similar to that outlined in Fig. 10B. Figure 11B provides an example
448 of such an increase, in which the “T3” bi-pulsed turbidite found at the 12PC location in the
449 upstream Juan de Fuca channel is correlated with a tri-pulsed T3 at the 25PC location in the
450 downstream Cascadia channel. The thickest interval of coarse sediments at 25PC is attributed
451 to a single pulse flow component derived from the Willapa channel that mixed with a bi-
452 pulsed flow from the Juan de Fuca channel (Fig. 11B; Gutiérrez-Pastor *et al.*, (2013).
453 Gutiérrez-Pastor *et al.*, (2013), Goldfinger *et al.*, (2008), Goldfinger *et al.*, (2012) and Patton
454 *et al.*, (2015) recognize that the pattern of pulsing seen in the majority of Holocene and late

455 Pleistocene turbidites correlated along the Cascadia margin appears to be consistent within
456 each deposit. They interpret the multi-pulsed character of these beds to indicate flow
457 initiation by the large magnitude ($M > 9$) seismic events that characterize this margin. In this
458 interpretation the apparent spatial persistence of pulsing character is contrary to the
459 expectation of pulse merging described above. Either the pulses arise another way, the pulse
460 merging phenomenon observed at laboratory scale does not occur within larger scale
461 turbidity currents, or the merging length scale in such natural settings is longer than the
462 spacing of sample locations. Further work is required to assess these possible explanations.

463

464 5. CONCLUSIONS

465 Physical modelling of multi-pulsed, solute density flows suggest that under most
466 circumstances individual pulses within such flows must be advected forwards through the
467 flow until they merge with the flow head. In natural dilute particulate gravity currents
468 (turbidity currents), such pulsing flow structure may be acquired at flow initiation and be
469 represented in any deposits by an interval of inverse grading (i.e., upwards coarsening) for
470 each pulse. Assuming that such pulses are progressively advected towards the flow front with
471 natural turbidity currents, a progressive reduction in the time between pulses is expected in
472 progressively more distal locations, eventually decreasing to zero when the pulse merges with
473 the flow head. Therefore an original pulsing signal might be relatively accurately preserved
474 proximally, become progressively distorted up to the point of merging where the signal is
475 completely lost ("signal shredded"). This may explain why normal grading is the predominant
476 turbidite grading style in distal locations. Pulsing flow character may also arise when
477 synchronously triggered flows combine at confluences; forward pulse advection will also
478 progressively distort then shred pulses of this character. In natural settings, such as the
479 Cascadia margin, the development of flow pulsing has already been inferred from the grading
480 patterns within turbidites deposited downstream of confluences. The possibility that multi-
481 pulsed flows may evolve spatially to become uni-pulsed can be invoked in studies of turbidites
482 deposited on the southwest Sumatra margin, and permits a wider range of potential
483 correlations to be considered. The multi-pulsed saline flows presented in this paper show
484 that pulse merging is effectively inevitable whilst interacting primary and secondary pulses
485 remain active. Given that waning flows suggest upward fining deposition and waxing flows

486 suggest the opposite, the extrapolation to predict the depositional patterns of pulsed
487 turbidites appears reasonable. Nevertheless, the extrapolation should ideally be supported
488 by experimental models of sediment-bearing flows together with a scaling analysis to more
489 robustly link the characteristic lengths of pulse merging at laboratory scale and those at
490 natural system scale; both are the subject of ongoing work.

491

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500

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687

688 **FIGURE CAPTIONS**

689 **Fig. 1:** Schematic sedimentary log of a turbidite with intervals of inversely graded grain size.
690 Inverse grading in pulsed deposits is distinct from basal inverse grading, which can be
691 produced by other mechanisms (e.g. Hand, 1997). Note: S = Silt; VF = very fine sand; F = fine
692 sand; M = medium sand; C = coarse sand; VC = very coarse sand; G = granules. Mudstone
693 clasts and hemipelagites are not always present.

694 **Fig. 2:** Schematic of the experimental set up. A 5 m-long flume with two lock boxes (each
695 0.125m long) set up in series at one end to enable the delayed release of a second pulse to
696 generate a pulsed flow. Two overspill boxes were used to reduce the effect of returning waves
697 associated with slumping of dense fluids in the lock boxes. Acoustic-Doppler Velocimetry
698 (ADV) was used to collect velocity data at successive downstream positions located at 0.365,
699 0.465, 0.585, 0.675, 0.765, 0.865, 0.965, 1.065, 1.265, 1.465, 1.665 and 1.865 m.

700 **Fig. 3:** Photographs of the flow at different time intervals for (A) a single-pulsed flow
701 experiment with 0 second delay time and (B) a multi-pulsed flow experiment with 4 second
702 delay time between two pulses. In (B) the two pulses completed merged between 15s and
703 18s. Gridlines on the bottom of the flume were used for camera alignment and flow position
704 tracking. Inset shows the advection of the second pulse within the first pulse.

705 **Fig. 4:** Plots showing the location of the front of (A) a single-pulsed and (B) a multi-pulsed flow
706 over time. Dashed curves are best fits of front position data collected from multiple
707 experiments.

708 **Fig. 5:** Contour plots showing spatio-temporal variation of internal velocity structure within
709 (A) a single-pulsed flow and (B) a multi-pulsed flow at 0.365 m, 0.675 m, 0.865 m, 1.265 m
710 and 1.665 m downstream from the back of the lock box. Red and blue lines between plots
711 indicate the arrivals of the primary and secondary pulses, respectively; these become
712 progressively closer with time in multi-pulsed flows. Note that the low velocity variations that
713 appear as vertical stripes of amplitude ($< 0.025 \text{ ms}^{-1}$) show the effect of surface waves, white
714 horizontal stripes in each subplot are areas of no data.

715 **Fig. 6:** Contour plots showing spatio-temporal variations of depth-averaged velocity of (A)
716 Single-pulsed flows and (B) Multi-pulsed flows. Note: Dashed and dotted curves are best fits
717 of front positions of primary and secondary pulses respectively.

718 **Fig. 7:** Comparison between depth-averaged velocity profiles of single- and multi-pulsed flows
719 at three different downstream positions: (A) Raw data and (B) Filtered data. Note: Raw data
720 were filtered by using Savitzky-Golay smoothing process in MatLab with a polynomial order
721 of three and a framelength of 151.

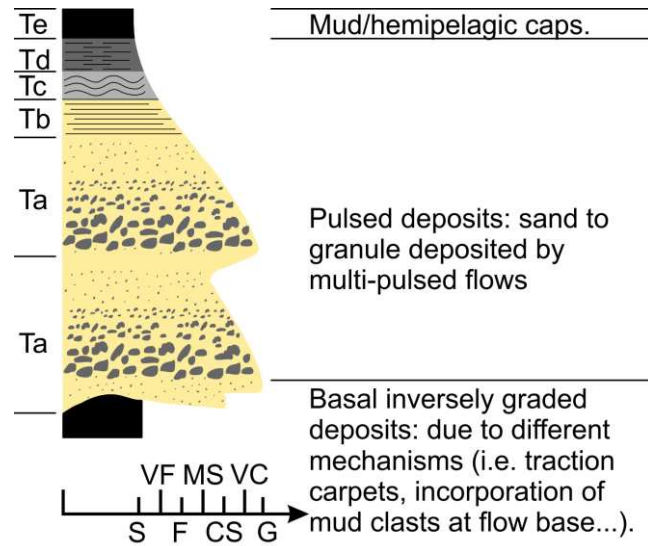
722 **Fig. 8:** Model of multi-pulsed flow propagation based on experimental results. Vertical axis
723 shows flow height (h), horizontal axes show density (d) and velocity (v). Note: The model
724 illustrates the scenario in which the second pulse intrudes into the first pulse at neutrally
725 buoyant level (see text for discussion of alternative scenarios).

726 **Fig. 9:** Conceptual models illustrating the depth-averaged velocity-time profile for various
727 turbidity current configurations and their inferred deposits. (A) A single-pulse turbidite with
728 an upward fining grain size profile. (B) Stacked turbidites comprising two single-pulsed
729 turbidities with a presence of Bouma Te (silt or clay layer) in between. (C) Amalgamated
730 turbidite with sharp interface between different inverse-to-normal grading cycles due to the
731 erosion of a latter flow into the deposit of an earlier flow. (D) Pulsed turbidites at relatively
732 proximal and distal locations. Note: 1) the lack of linear correspondence between the time
733 and depth records (shown schematically for Fig. 9A, and implied for 9B-D); 2) pulsed turbidites
734 might have internal erosion surfaces instead of (or in addition to) inverse grading depending
735 on pulse strength.

736 **Fig. 10:** Initiation mechanisms of multi-pulsed flows: **(A)** Multi-pulsed flow triggered by
737 retrogressive slope failures and conceptual turbidite patterns for longer vs. shorter failure
738 delays in the left-hand and right-hand panels, respectively and **(B)** Tri-pulsed flow triggered
739 by flow combination at channels, and possible turbidite grading patterns.

740 **Fig. 11:** Multi-pulsed turbidites **(A)** offshore Sumatra at the 4MC and 2MC core locations
741 (modified after Sumner *et al.*, 2013), dashed curve shows proposed channel conduit and **(B)**
742 in the linked Juan de Fuca and Cascadia channels at the 12PC and 25PC locations (modified
743 from Gutiérrez-Pastor *et al.*, 2013), white curve shows channel conduit (Goldfinger *et al.*,

744 2016). Note: because grainsize was estimated directly from the core, sediments finer than 62
 745 μm cannot be distinguished (A). Magnitude of magnetic data reflect grainsize of turbidites.
 746 Bathymetric data were taken from GebCO, 2014.

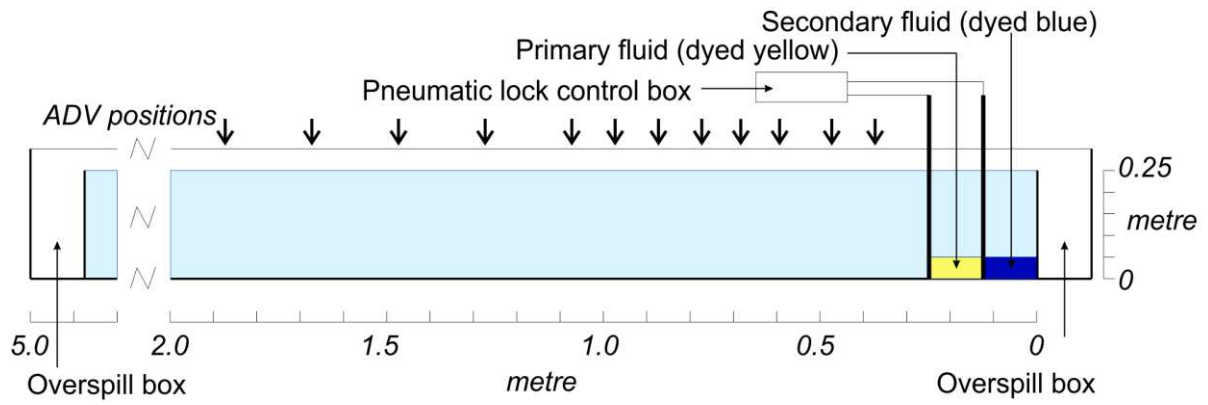


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748 Figure 1

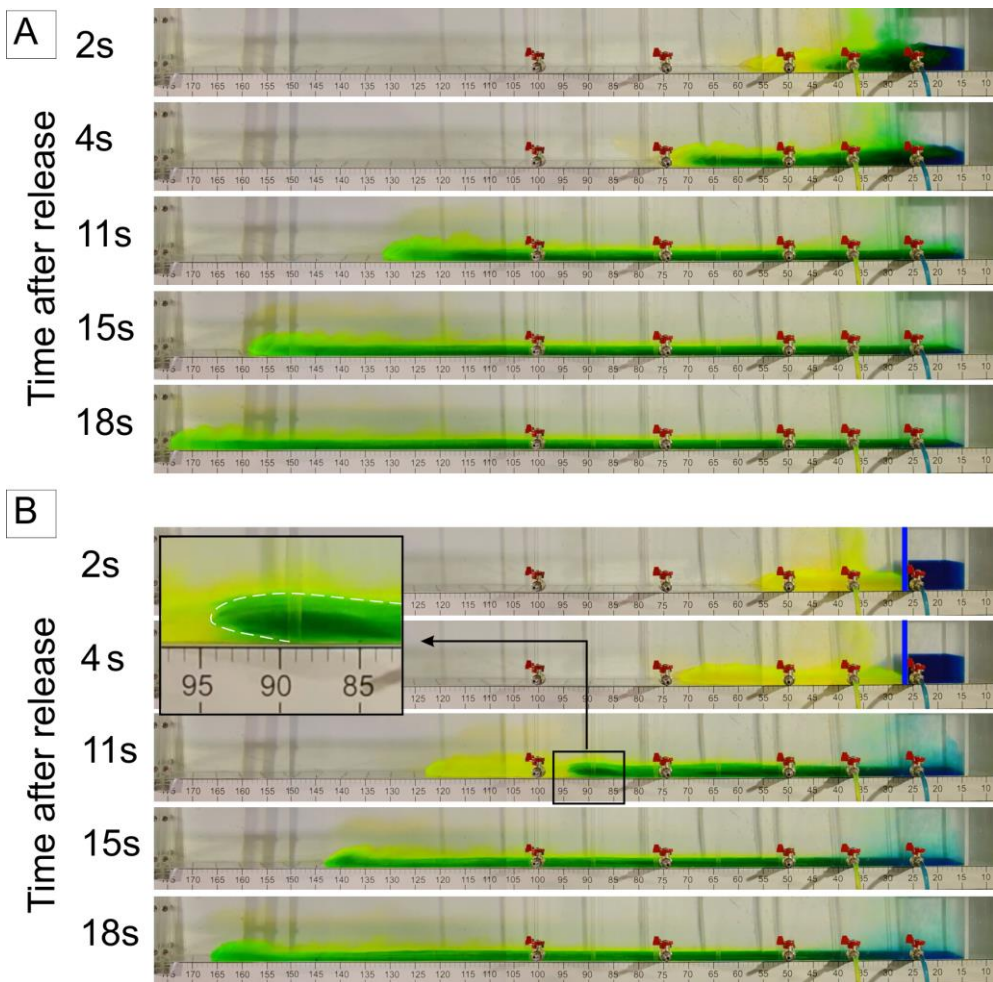
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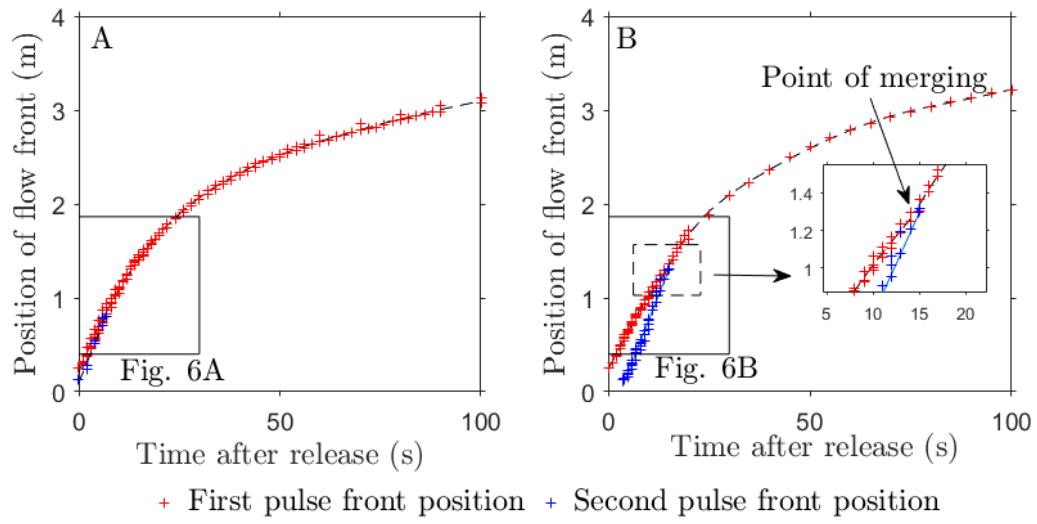
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752 Figure 2



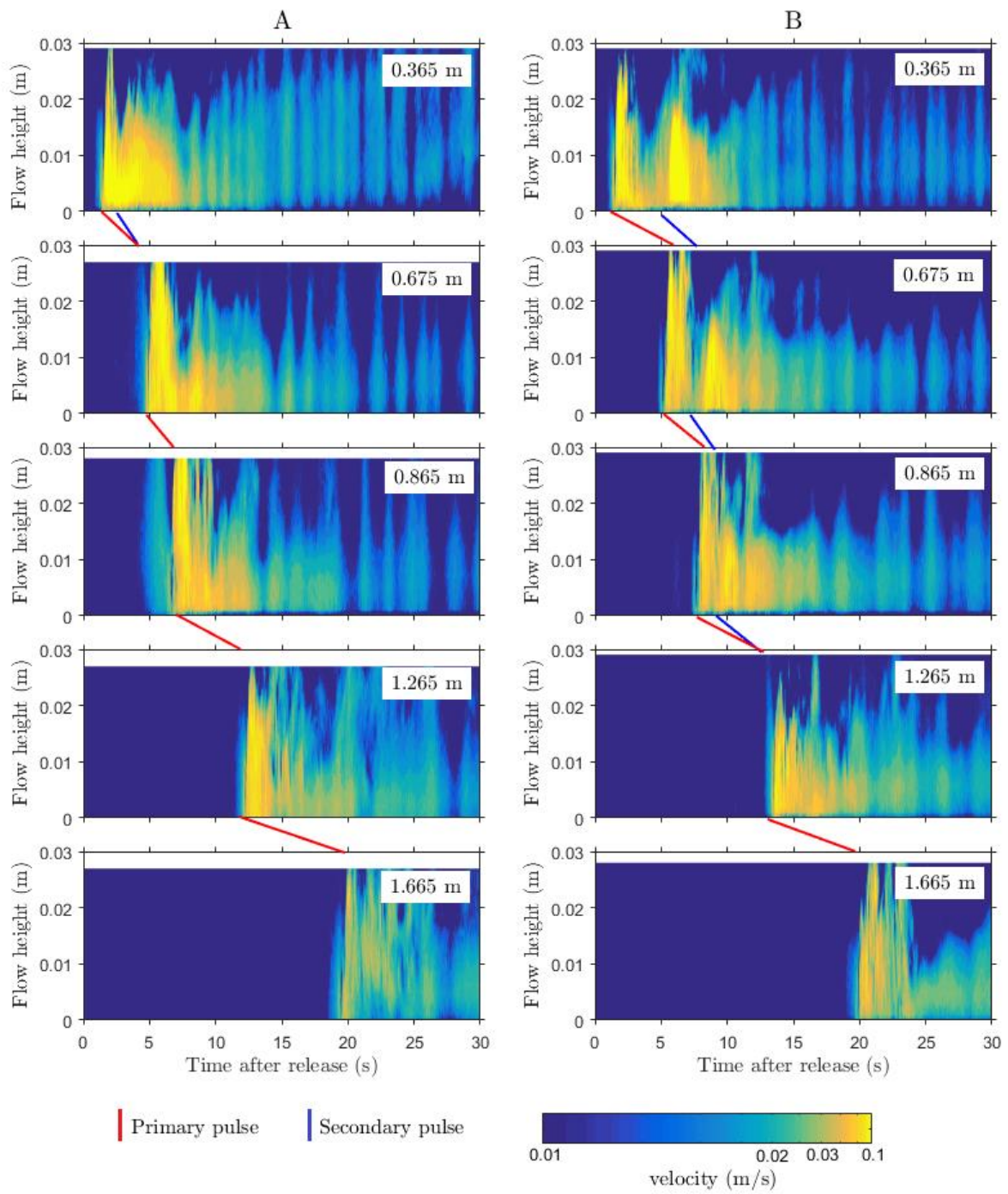
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754 Figure 3



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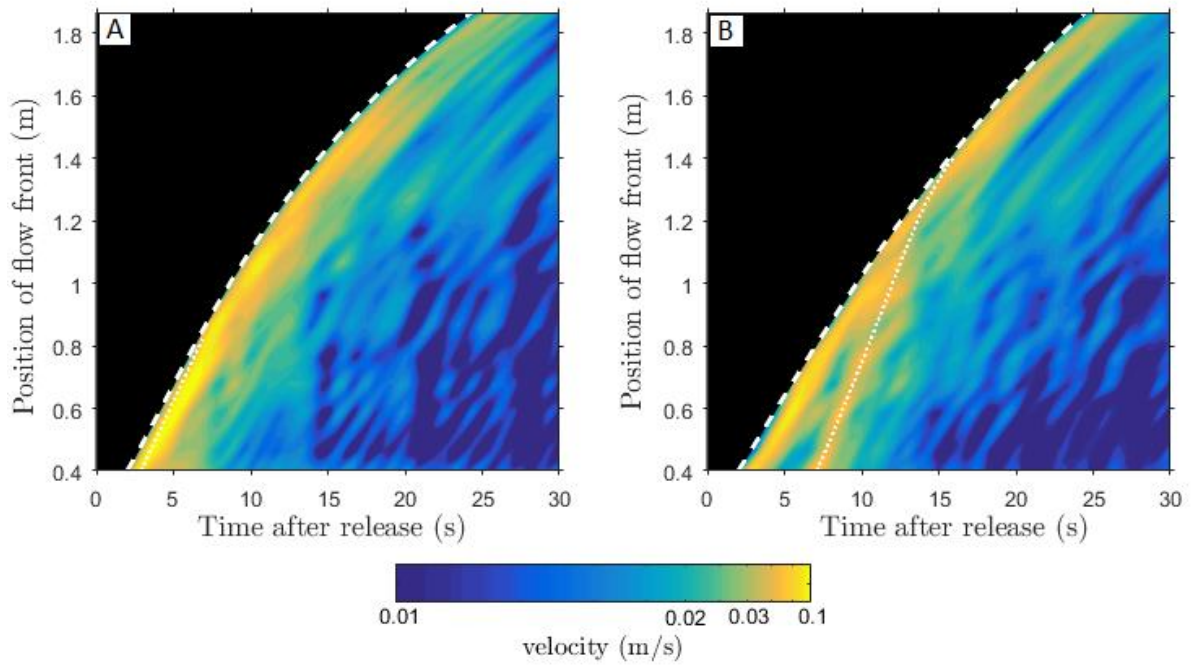
756 Figure 4



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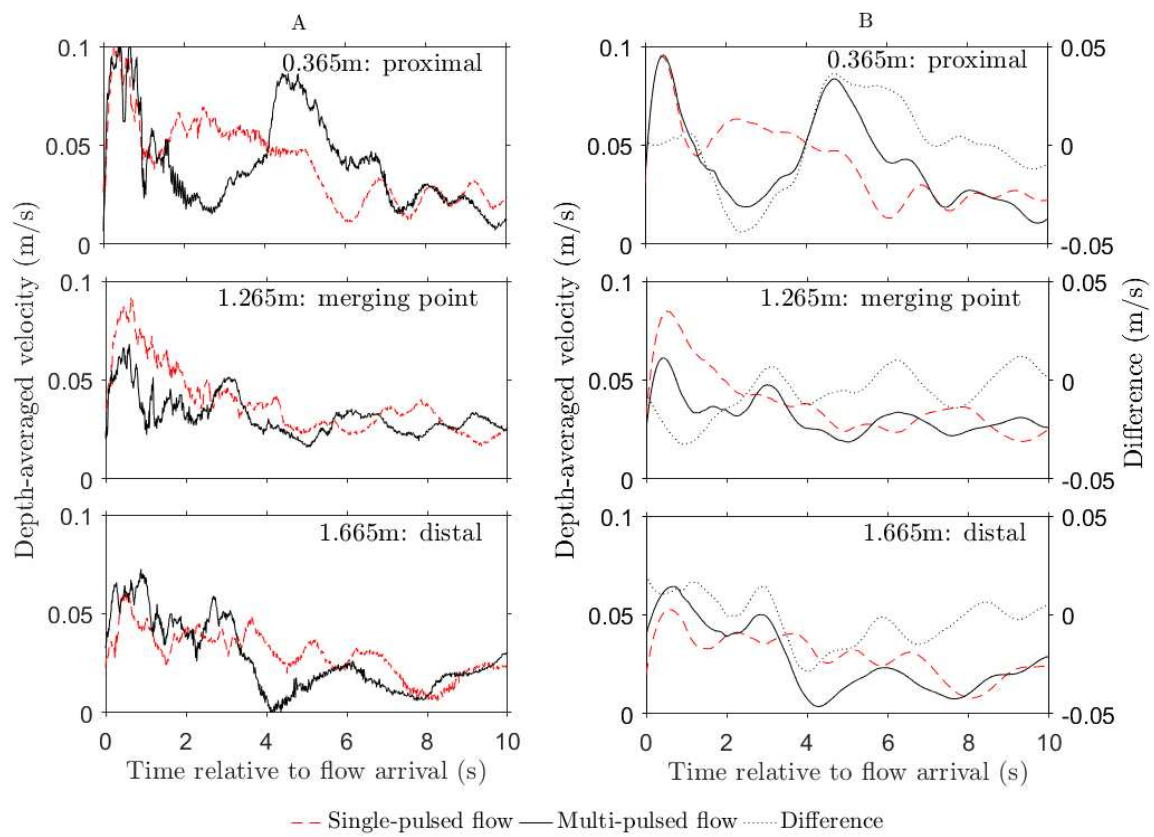
758 Figure 5

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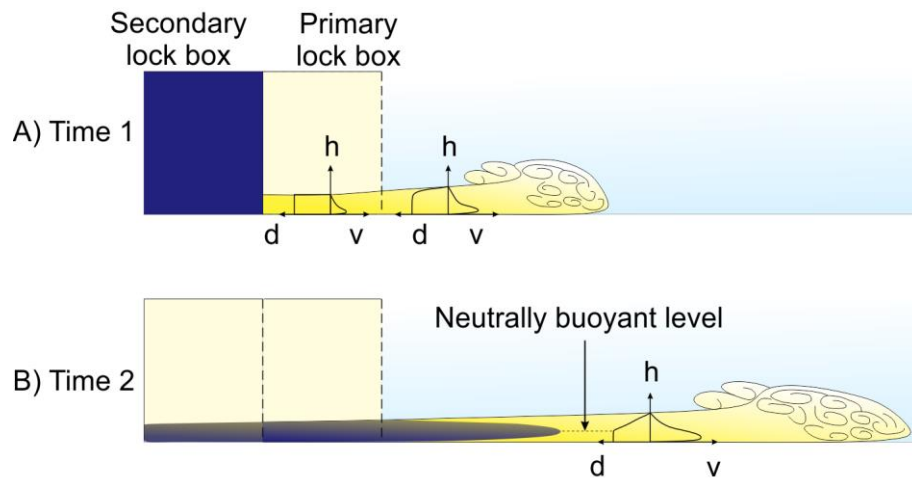
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761 Figure 6



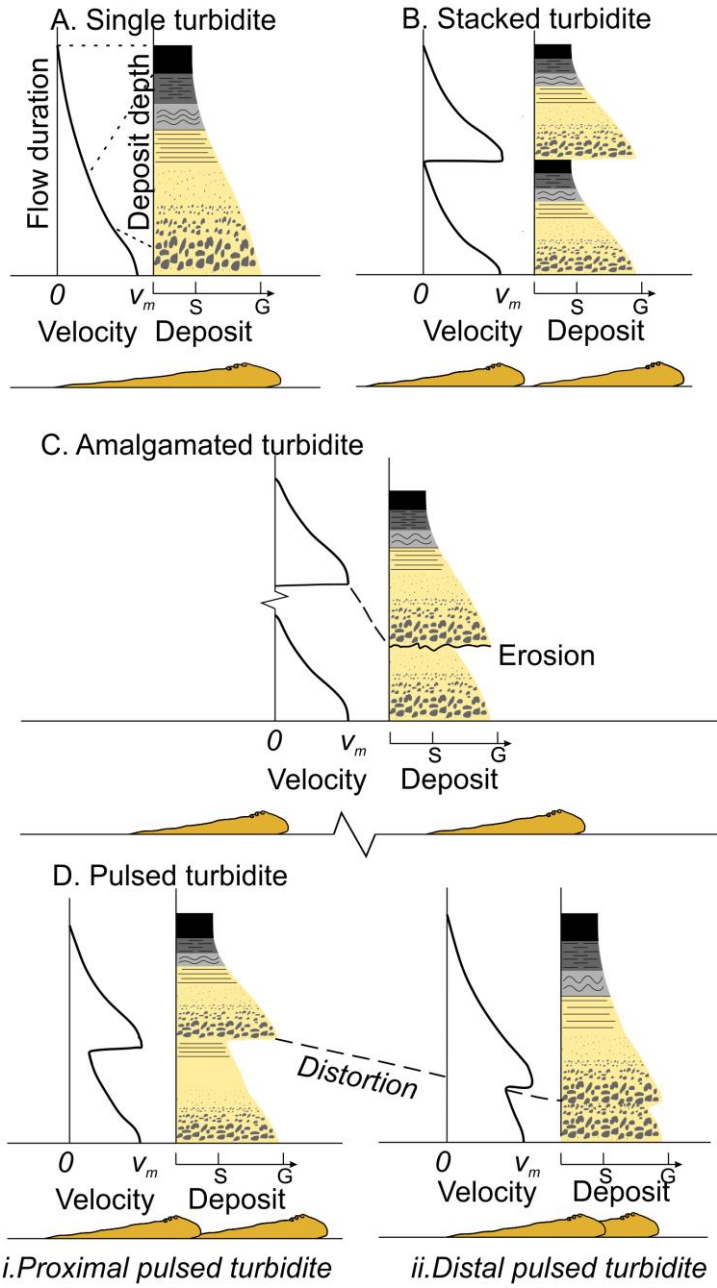
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763 Figure 7



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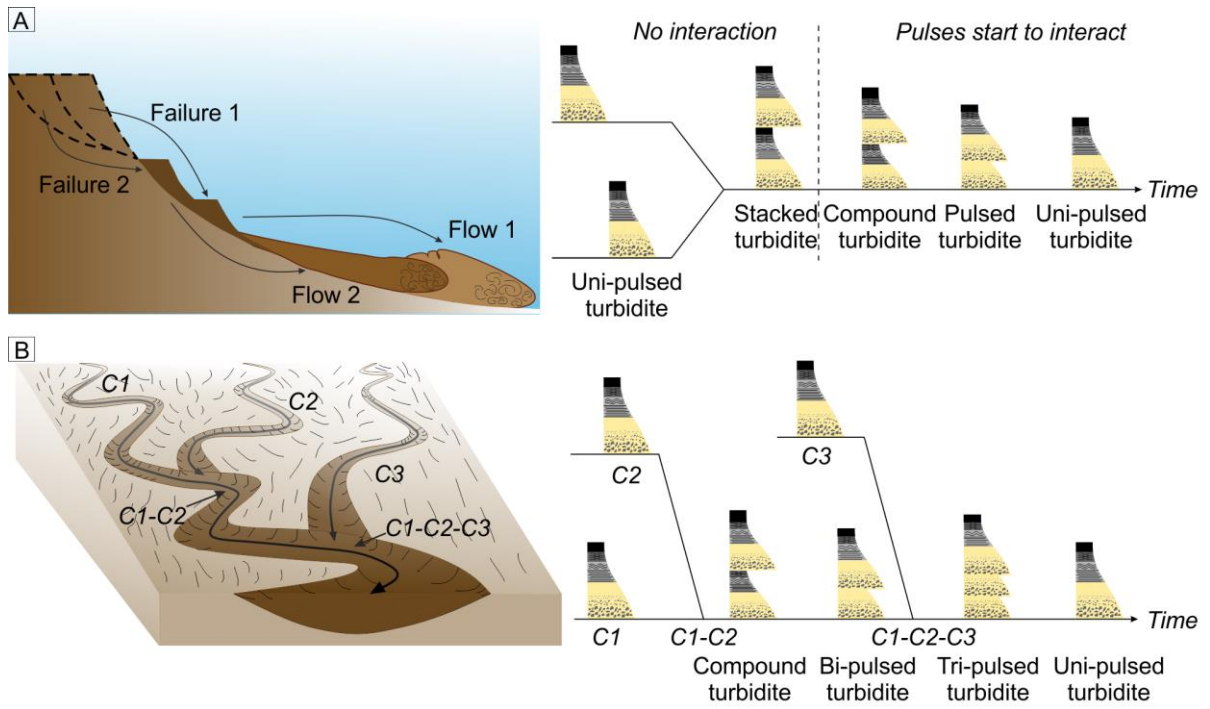
765 Figure 8



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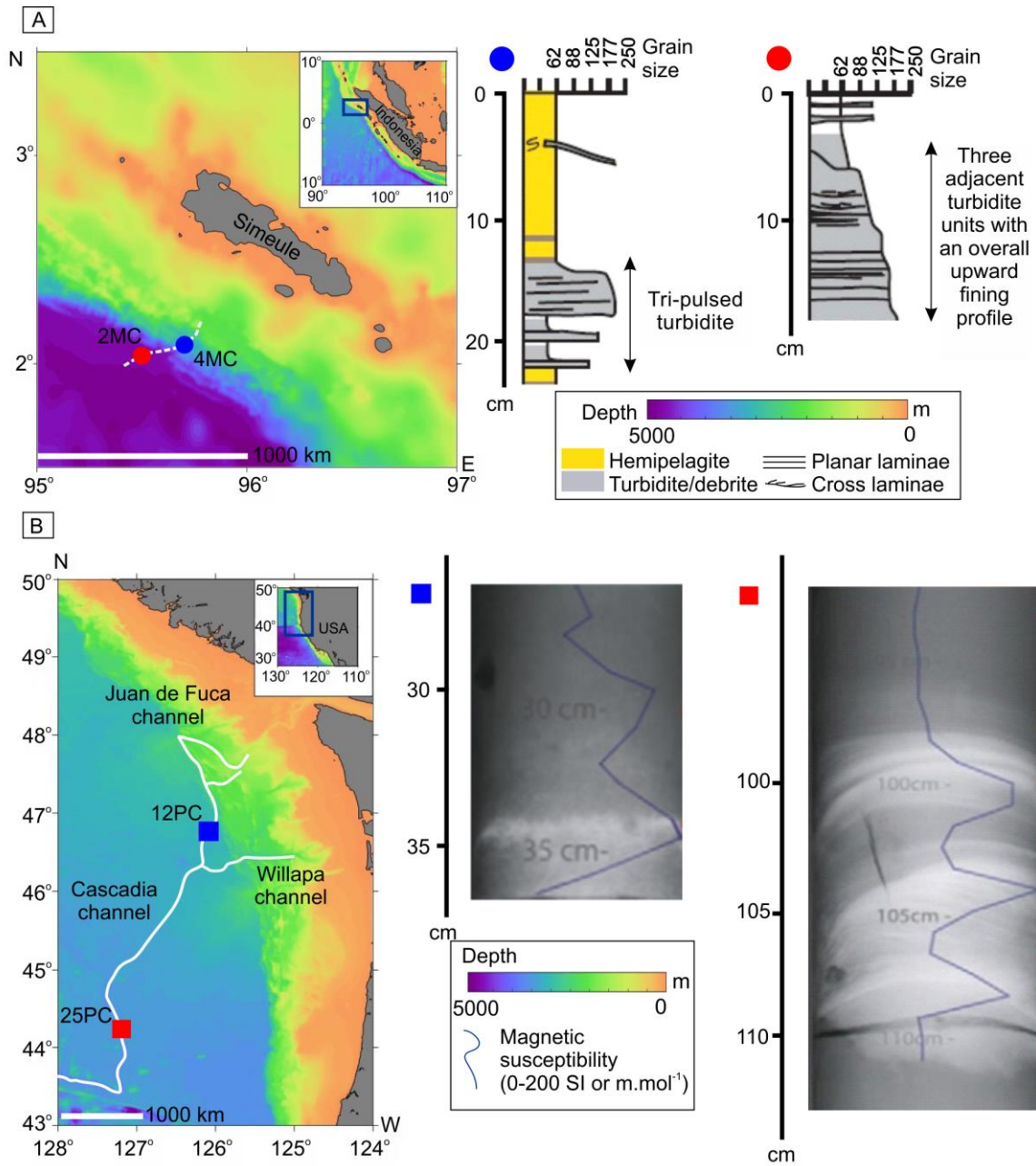
767 Figure 9

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769

770 Figure 10



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772 Figure 11