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1 DYNAMICS AND DEPOSITION OF SEDIMENT-BEARING MULTI-PULSED FLOWS AND 2 GEOLOGICAL IMPLICATION

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14

ABSTRACT

15 Previous studies on dilute, multi-pulsed, subaqueous saline flows have demonstrated that 16 pulses will inevitably advect forwards to merge with the flow front. On the assumption that 17 pulse merging occurs in natural-scale turbidity currents, it was suggested that multi-pulsed 18 turbidites that display vertical cycles of coarsening and fining would transition laterally to 19 single-pulsed, normally-graded turbidites beyond the point of pulse merging. In this study, 20 experiments of dilute, single- and multi-pulsed sediment-bearing flows (turbidity currents) 21 are conducted to test the linkages between downstream flow evolution and associated 22 deposit structure. Experimental data confirm that pulse merging occurs in laboratory-scale 23 turbidity currents. However, only a weak correspondence was seen between longitudinal 24 variations in the internal flow dynamics and the vertical structure of deposits; multi-pulsed deposits were documented, but transitioned to single-pulsed deposits prior to the pulse merging point. This early transition is attributed to rapid sedimentation-related depletion of the coarser-grained suspended fraction in the laboratory setting, whose absence may have prevented the distal development of multi-pulsed deposits; this factor complicates estimation of the transition point in natural-scale turbidite systems.

30 INTRODUCTION

Turbidity currents are dilute, subaqueous particle-laden gravity currents (Middleton 1993; Piper & Savoye 1993; Huppert 1998; Xu et al. 2004). They commonly initiate on continental shelves and transport significant volumes of sediment from the continents to deep marine environments (Simpson 1982; Talling et al. 2015), where they build the most spatially extensive sedimentary landforms on the planet (Canals et al. 2004; Xu 2011; Dorrell et al. 2015; Lintern et al. 2016).

37 Turbidity current deposits - turbidites - can be used to infer the dynamics of the 38 overpassing flows (Hand 1997; Goldfinger et al. 2012; Kneller & McCaffrey 2003). Turbidites 39 are formed as turbidity currents decelerate and material is deposited from suspension. 40 Because particle-transport competence (i.e., the maximum particle-size that can be transported) decreases as flow wanes (Dorrell et al. 2013), turbidites commonly exhibit 41 42 classic upward-fining grading structures. These "single-pulsed" turbidites are thus 43 interpreted to reflect a single depositing turbidity current event (Hand 1997; Kneller & 44 McCaffrey 2003; Amy et al. 2006; Dorrell et al. 2011a; Stevenson et al. 2013). However, 45 "pulsed" or "multi-pulsed" turbidites characterised by repeated cycles of inverse-to-normal grading (with or without grain size breaks) are also seen higher up within a single event-bed 46 47 in real world environments (Goldfinger et al. 2012; Stevenson et al. 2014; Van Daele et al. 48 2017). This feature is different from the inverse-graded intervals which characterise many 49 turbidite bed bases (see Hand 1997). Multi-pulsed turbidites are therefore thought to be 50 deposited by turbidity currents whose longitudinal velocity structures show repeated patterns of waxing-waning mean velocity, and thus variations in flow capacity and 51 52 competence (Dorrell et al. 2013, 2018; Stevenson et al. 2014). Such currents can be 53 initiated by: i) retrogressive submarine slumping occurring due to sequential earthquake 54 faulting or shock/aftershock events; ii) combination of multiple single-pulsed flows sourced 55 in different upstream areas at downstream confluences (Goldfinger et al. 2012; Ismail et al. 56 2016; Beeson et al. 2017; Johnson et al. 2017); and iii) variation in discharge rates of 57 sediment fluxes from fluvial systems into the oceans (Mulder & Alexander 2001).

58 Experimental data describing the dynamics of multi-pulsed saline gravity currents, presented in Ho et al. (2018a) and Ho et al. (2018b), suggest that initially multi-pulsed 59 60 velocity structures transform into standard waxing-waning profiles as flows run out. The 61 principal implication was that any associated turbidites would likely exhibit multi-pulsed 62 grading profiles relatively proximally to the source, but that the deposits would become 63 normally graded past the point where pulses within the flows merge completely. A second 64 implication was that, approaching this point, the spatial separation between multiple cycles of inverse-to-normal grading within a single turbidite would progressively reduce, reflecting 65 the progressive reduction in the temporal separation between multiple velocity pulses. 66 67 These implications are based on the assumptions that: a) normally graded turbidite intervals 68 are deposited in the waning phase of flows and non-deposition or the deposition of upward-69 coarsening turbidite intervals is expected during the waxing phase (Kneller & Branney 1995; 70 Hand 1997; Kneller & McCaffrey 2003; Amy et al. 2005; Basilici et al. 2012); b) flows are 71 depositional from the outset, with flow conditions being recorded in the deposit during 72 progressive aggradation (Basilici et al. 2012; Goldfinger et al. 2013); c) a wide enough range

of grain sizes is carried in suspension for a link between the flow shear stress and grain size to be expressed in the deposit (Dorrell et al. 2013); and d) that there is sufficient time for the suspension to respond to changes in flow conditions (Dorrell & Hogg 2011b).

76 Questions regarding the variation of flow dynamics in sediment-bearing multi-pulsed 77 flows and their expression in depositional structures along flow pathways include: i) 78 whether the merging phenomenon observed in the saline flow experiments can be 79 reproduced for multi-pulsed turbidity currents; ii) whether any grading patterns within 80 deposits can be discerned; and iii) whether linkages can be established between real-time 81 suspension structures of sediment within the flows and depositional grading patterns. To 82 address these questions, this paper details the first experiments conducted to model multi-83 pulsed sediment-bearing flows, focusing on the difference in dynamics between single- and 84 multi-pulsed turbidity currents linked to the vertical grading profiles of their deposits.

85 **METHODOLOGY**

86 Experimental Set-up and Parameters

87 Experiments were conducted in a 5 m-long flume with two 0.25 m-long lockboxes set-up at 88 one end (Fig. 1). This set up of the lockboxes enabled the generation of two pulses in series. 89 Both single- and multi-pulsed flows entailed release of flow pulse components of the same 90 volume. Using electronically-timed pneumatic rams, the timing between the two lock gate 91 release was set at 0 s, 2.5 s and 8 s in order to model two flow types, i.e., single- and multi-92 pulsed flows. It should be noted that by 2.5 s after the first lock gate was withdrawn, the 93 returning wave generated by the collapse of the first dense fluid had not reached the back 94 of the first lockbox such that the dynamical variations between the 0 s and 2.5 s delay time 95 flows were expected to be minimal (see section 3.1 and Ho et al. 2018b for discussion). 96 Therefore, both 0 s and 2.5 s delay time flows were effectively single-pulsed flows, whereas

97 an 8 s delay time enabled the generation of multi-pulsed flows. The dense fluid used for the 98 flows was made of a mixture of fresh water and 625 g of suspended sediment consisting of 99 both spherical Ballotini and Spheriglass in the ratio 4:1 by weight; sediment size ranged between 5 and 120 μm (see Appendix A). The density of sediments was 2500 kgm⁻³ (Potters 100 101 2018). This combination of sediments gave the suspension an initial excess density of 3.75%, 102 corresponding to a volumetric concentration of 2.5%. Sediments in the lockboxes were kept in suspension by using two MESE^R overhead stirrers that were set to run at 1000 rpm at the 103 104 start of the experiments. Each mixer was fitted with a switch that automatically stopped it 105 as the gate in front was lifted (Fig. 1). The depth of fluid contained in the two lockboxes and 106 of freshwater in the flume was 0.20 m. The flow component in the second lock was dyed 107 blue in order to enhance the visualisation of the flows. In order to confirm that pulses 108 within the multi-pulsed flows eventually merged, the front positions of two pulses were 109 tracked separately using two moving cameras which were set on a track in front of the 110 flume (method after Ho et al. 2018b).

111 Experimental Approach and Data Processing

112 **Profiling Acoustic Doppler Velocimetry**

113 Two acoustic Doppler velocity profilers (Nortek Vectrino Profilers; aDvps) were deployed to 114 measure time-series velocity fields at positions 1.7 m, 2.7 m and 3.7 m along the flume (see 115 Fig. 1). The probes were mounted vertically on two rods spaced 0.1 m apart in the 116 streamwise direction, the two probes were synchronised using Nortek's MIDAS data 117 acquisition software (Nortek 2015) and set to collect velocity profiles at 100 Hz until the flow ceased. The upstream transducer was mounted 81 mm above the channel floor (i.e., 118 119 bottom of the tank) and recorded the velocity profile in 21, 1 mm-high, cells between 19.5 120 mm and 40.5 mm above the bottom of the tank. The downstream transducer was mounted

121 61 mm above the channel floor and recorded the velocity profile in 21, 1 mm-high, cells 122 between 0 mm and 20.5 mm above the floor (see Fig. 1). The vertical overlap between the 123 sampling regions of the two probes was 1 mm. Prior to lock release, the ambient fluid in 124 front of the aDvp probes was seeded with neutrally-buoyant hollow glass spheres of 10 μm 125 diameter (Sphericel 110-P8) to raise the Signal-to-Noise Ratio to at least 25 dB (see Thomas 126 et al. 2017). Two sets of aDvp data were collected in each experiment, measuring the 127 velocity field of the upper and lower halves of the basal 40 mm of flow. These data sets 128 were merged to visualise the velocity field within the whole flow. Streamwise velocity data 129 were plotted as a series of isovel maps that displayed spatio-temporal variations of velocity 130 within the basal 40 mm of flow for each current. Depth-averaged velocities were also 131 calculated for both data sets (method after Ho et al. 2018a, averaging over 20 mm). The lateral offset of 0.10 m between the two aDvp probes (see inset, Fig. 1) resulted in a 132 133 temporal displacement in the two data sets collected, such that within the first ~2 seconds 134 of any sampling period only velocities within the top half of the basal 40 mm of flow were 135 captured. This is because the flows always arrived at the upper aDvp probe first.

136 Focused Beam Reflectance Measurement (FBRM)

137 In order to quantify the particle size distributions (PSD) within the experimental flows, a 138 Focused Beam Reflectance Measurement system (FBRM) was deployed. FBRM uses a rotating laser beam to measure the chord length distribution (CLD) of all the particles 139 140 present within the measurement window every two seconds over a defined time period 141 (e.g., Wynn 2003; Greaves et al. 2008; Agimelen et al. 2015). The CLD were then converted to PSD using the conversion method of Wynn (2003), which assumes that all the sediment 142 143 particles are spherical. The FBRM was deployed so that the centre of the measurement 144 window was located 20 mm above the channel floor, the approximate height of the velocity 145 maximum as noted in earlier experiments. FBRM data were acquired at 1.85 m, 2.85 m and 146 3.85 m along the flume (Fig. 1). The FBRM probe was deployed at an inclination of 45°, 147 pointing upstream in order to effectively capture the arrival of suspended particles (see 148 inset, Fig. 1). This configuration minimised the stagnation zone between the measurement 149 window and the flow (set up recommended by the manufacturer, Mettler-Toledo 2013). 150 The cross-sectional area of the 30 mm diameter FBRM probe was relatively small such that 151 it did not interfere with the evolution of the flows at the point of measurement. In addition, 152 no measurements were taken downstream of positions where the FBRM probe was set up.

153 Sediment data

154 Deposits were sampled and analysed for the 2.5 s and 8 s delay time flow experiments in 155 order to compare their depositional structures; as noted above the 2.5 s delay time deposits 156 effectively represent a single-pulsed turbidite. Deposits were collected at positions 0.7 m, 1.7 m, 2.7 m, 3.7 m and 4.7 m downstream. Five pieces of 0.25 mm-thick acetate sheet of 157 158 dimensions 0.12 m by 0.12 m were glued on the bottom of the flume at the positions where 159 deposits were to be sampled; sediment was deposited on top of these sheets. Once the 160 sediments had completely settled (after two days), ambient water was slowly discharged 161 from the flume by siphoning. Plastic rings of 0.10 m diameter were placed onto the acetate 162 in order to secure the deposits. The sediment samples were further allowed to fully dry at 163 room temperature over two days before careful removal from the flume. Each dry sample 164 was impregnated with low-viscosity two-part adhesive under partial vacuum and mounted 165 into transparent cubes. The surface of the mounted samples was polished, and carbon coated to enable imaging using a Tescan VEGA3 Scanning Electron Microscope (SEM). 166 167 Grading trends were sufficiently subtle to not be immediately evident from visual inspection, necessitating an image analysis approach. Therefore, the SEM images were 168

169 processed using MatLabTM 2016, using code based on the Granulometry of Snowflakes example 170 (Mathworks 2018) to calculate grain size. In brief, on each image this entailed performing 171 morphological opening operations using circular structuring elements of progressively 172 increasing size and then differentiating the resulting pixel counts to yield the number of 173 pixels associated with each size circle. Finally, the results were scaled and classified into $\frac{1}{2}\varphi$ 174 classes.

175 **RESULTS**

176 Visualisation

The single-pulsed (0 s and 2.5 s delay time; Figs. 2 and 3) and multi-pulsed (8s delay time; Fig. 4) flows evolved in a similar manner to single- and multi-pulsed saline flows (see Ho et al. 2018a and Ho et al. 2018b for details of the flow visualisation approach). Hereafter, both 0 s and 2.5 s delay time flows are referred to as single-pulsed flow and 8 s delay time flow is referred to as multi-pulsed flow.

182 Velocity Data

183 Single-pulsed Flow (0 s and 2.5 s delay time)

The velocity profiles of these flows exhibited a normal waxing-waning velocity structure as commonly observed in laboratory and field-based data (Figs. 5A-B & 6A-B; e.g., Simpson 1982; Kneller et al. 1999; Lowe et al. 2002; Cooper et al. 2013; Sher & Woods 2015; Ho et al. 2018a, 2018b). The velocity maximum was located within the bottom 40 mm of the flow (Figs. 5) with body velocities higher than those of the flow fronts. The flows decelerated downstream (Figs. 5A-B). The thicknesses of the heads were also seen to decrease with increasing time.

191 Multi-pulsed Flow (8 s delay time)

192 Proximal to the source, two distinct pulses were seen in the velocity structure of the flow 193 (Figs. 5C and 6C, x=1.7 m). The second pulse travelled at higher velocity than that of the first 194 pulse (Figs. 5C, x=1.7 m). Further downstream, the first pulse decelerated while the second 195 pulse maintained a relatively high velocity which enabled it to catch up with the first pulse 196 (Figs. 5C and 6C, x=2.7 m). The separation between the two pulses was progressively 197 reduced over time such that the pulses eventually merged (Figs. 5C and 6C). Flow 198 visualisation data captured during the experiments suggest that pulses within the 8 s delay 199 time flow merged at 4.05 m from source (i.e., at the position x=4.20 m shown on the 200 gridline, Figs. 1 and 4). However, due to space constraints at the end of the flume, aDvp 201 data could not be collected beyond 4.0 m.

202 Sediment Suspension Profiles

In this section, profiles of sediment suspension at 20 mm flow height are described for the single-pulsed (0 s and 2.5 s) and the multi-pulsed (8 s) flows, respectively. The time-series patterns of sediment suspension at this characteristic height, measured at different downstream positions, are thought to be indicative of the temporal variations of sediment suspension at any given height within the flows. PSDs were bimodal in form at every time step, though the range of size classes varied in each data set (Fig. 7) as will be described below.

At proximal localities, the number of particles arriving at the sampling position progressively decreased as the heads passed by the probe (Figs. 4A-C, x=1.85 m). Particle counts were relatively stable within the bodies of the flows (Figs. 4A-C, x=2.85 m & x=3.85 m).

214 Single-pulsed Flow

215 Mean grain size gradually increased as the flow head passed by the sampling position. Initially, sediments of 20-60 μ m had been carried by the flow front over the first 5 s of the 216 217 sampling period, prior to the arrival of the body (Figs. 7A-B, x=1.87 m, 15-20 s). After the 218 passage of the heads, mean grain size (i.e., sizes of sediment ranged within 30-90 μ m) 219 started to increase, which marked the arrival and passage of the flow bodies. At further 220 distances, fine-grained sediments of 20-60 µm were always suspended in the flow fronts 221 (Figs. 4A-B, x=1.85 m, 13-20 s; x=2.85 m, 25-30 s; x=3.85 m, 32-36 s) whereas coarser 222 sediments of 30-90 μ m were carried by the body and the tail (Figs. 4A-B, x=1.85 m, 40 s; 223 x=2.85 m, 40 s).

224 Multi-pulsed Flow

225 Sediments of 20-60 μ m grain size were suspended in the flow front within the first 5 s after 226 the flow passed the probe; grain sizes then increased to range within 30-90 µm as the flow 227 head moved past the sampling position (Fig. 7C, x=1.85 m, 15-20 s). The arrival of a second 228 pulse was marked by a decrease in grain size (Fig. 7C, x=1.85 m, t=18 s). After the second 229 pulse front passed the probe, sediment grain size started to increase (Fig. 7C, x=1.85 m, t=21 230 s). Similarly, at x=2.85 m, the suspended sediment grain size within the flow front increased 231 as the first pulse arrived but decreased as a second pulse started to intrude into the first 232 pulse (Fig. 7C, x=2.85 m, 33-40s). Further downstream, at the position where the two pulses 233 were close to merging, the range of grain size remained relatively constant (Fig. 7C, x=3.85 234 m).

235 Sediment Data

In this section, data describing depositional structures of single-pulsed (2.5 s delay time) and
multi-pulsed (8 s delay time) flows are presented in the order of i) trends observed for all
deposits and ii) different features in depositional profiles of each flow type.

239 The experimental data showed that thicknesses of the deposits collected in the 240 experiments decreased as the flows travelled further from the source (Fig. 8). This observation corroborates previous studies (e.g., Kneller & Branney 1995; Mulder & 241 242 Alexander 2001; Harris et al. 2002; Shanmugam 2002). For each experiment (i.e., each flow 243 type), data detailing the vertical variations in grainsize of fine, median and coarse sediment 244 fractions (i.e., d16, d50 and d84) showed similar trends (Fig. 8, d16, d50 and d84 for each 245 flow type at five sampling positions). Basal inverse-graded deposition was observed for the 246 deposits of both flow types (Fig. 8) and was attributed to longitudinal grain size segregation (Hand 1997; Baas et al. 2004). Above the inverse-graded interval, normal grading was 247 248 generally developed, with an abrupt reduction in the fining-up gradient occurring at about 249 two-thirds deposit height.

250 Single-pulsed Flow

All deposits collected in the single-pulsed flow experiment exhibited upward-fining grading profiles after the basal inversely-graded interval (Fig. 8, data indicated by blue line; cf., Kneller & McCaffrey 2003; Amy et al. 2005; Babonneau et al. 2010 for similar observations). The proximal deposit (0.7 – 1.7 m) was thicker than the deposit downstream (3.7 - 4.7 m) by approximately 50%. This observation of thicker deposits near the lock gates is commonly seen in lock-exchange sediment-bearing flow experiments and models (Fig. 8; Bonnecaze et al. 1993; Kneller & McCaffrey 2000; Peakall et al. 2001; Harris et al. 2002).

258 Multi-pulsed Flow

259 The thickness of the deposits sampled proximal to the source, at 0.7 m, 1.7 m and 2.7 m,

- was greater than that of deposits taken at distal locations by 50%. At 1.7 m, the flow
- 261 deposited proximal turbidites with a higher fraction of coarse sediments (Fig. 8C, 0.7 m).
- 262 Vertical grading of the coarse fraction deposited by this flow showed two intervals of

- inverse-to-normal grading (Fig. 8C, 0.7 m, red curve). It was noted that the pulses in the flow
- this experiment merged at 4.2 m down the flume, but the flow deposited sediments with
- simple upward-fining grading structures from at least 1.7 m (Fig. 8C).

266 **DISCUSSION**

267 The Initiation and Dynamics of Single- and Multi-pulsed Flows

268 To predict whether multi-pulsed flows will be generated, the timing interval 269 between pulses at initiation (i.e., between the release of successive lock gates, or between 270 two currents in natural settings) needs to be constrained. In the laboratory setting, the 271 minimum value for which a multi-pulsed flow is formed corresponds to the time taken for 272 the backwards-propagating wave generated upon the slumping of the first pulse to reach 273 the second lock gate, corresponding a distance of one lock length. If the wave has not 274 reached this gate before it is raised, the combined flow is the same as the instantaneous 275 release of a double-length lock (i.e., Figs. 5 and 6 show the dynamical similarity of the 0 s 276 and 2.5 s flows; see also Ho et al. 2018b). In prototype environments, delay time between 277 pulses may range from minutes to hours, or longer, depending on the nature of the 278 initiation mechanism (e.g., Hsu et al. 2008; Goldfinger et al. 2012; Lupi & Miller 2014; 279 Beeson et al. 2017). In the real-world, single-pulsed flows are generated either by a single-280 trigger event, or by two (or more) events whose temporal separation is insufficient to form 281 separate flow events.

Experimental data demonstrate that material from the body of both single- and multi-pulsed flows is eventually advected toward the flow fronts (Figs. 2-4). Advection of fluid within the body of dilute gravity currents towards the flow front is ubiquitous due to their internal velocity profiles (Lowe et al. 2012; Stevenson et al. 2013; Sher & Woods 2015; Hughes 2016). Therefore, single- and multi-pulsed flows cannot be distinguished by advection of material from back to front of the flow. The key criterion is the development of
one or more episodes of increasing then decreasing mean velocity in the multi-pulsed case
compared to the monotonic decrease in mean velocity seen in the single-pulse case (e.g.,
Figs. 5, 6).

291 Single-pulsed Flow Deposits

292 Deposits derived from single-pulsed flows are thicker closer to source than downstream, 293 e.g. deposits at 0.7-2.7 m were 50% thicker than those at 3.7-4.7 m (Fig. 8). In addition, a 294 high proportion of coarse-grained sediments are deposited proximally (Fig. 8; see also Middleton 1993; Gladstone et al. 1998; Kneller & McCaffrey 2003). In general, as suggested 295 296 by the experimental data (Fig. 8), single-pulsed flows deposit sediments with the expected 297 upward-fining grain size profile (e.g., Bouma 1962; Lowe 1982). Inverse grading in the basal 298 part of deposits is also seen (e.g., Fig. 8), probably reflecting the lagged arrivals at the head 299 of sediments with different grain size (e.g., Kneller & Branney 1995; Hand 1997). Sediment 300 suspension data from single-pulsed flows (Figs. 7A-B) indicate that relatively finer sediments 301 (20-60 μm) are carried by flow fronts, whereas coarser sediments (30-90 μm) are suspended 302 within the bodies. Although translation of these longitudinal variations in mean grain size 303 into grading profiles is apparently consistent with the lagged-arrival model of Hand (1997), 304 the FBRM data in this study were acquired 20 mm from the base of the flow, i.e., above the 305 depositional interface; it is likely that sediments carried below this level would have been 306 coarser grained due to the stratification commonly developed within turbidity currents (e.g., 307 McCaffrey et al. 2003; Baas et al. 2005; Dorrell et al. 2014; Ho et al. 2018a). Nevertheless, 308 on the assumption that relative temporal variations in grain size composition at any 309 particular level are likely representative of variations seen at lower levels, the lagged arrival 310 mechanism remains a viable explanation of basal inverse-graded interval formation. It is difficult to invoke other causes of inverse grading, such as a marked interval of waxing flow
(Kneller and McCaffrey 2003; Stevenson et al. 2014) or kinetic sieving within the basal flow
layer under low deposition rates (cf. Sumner et al. 2008) as the single-pulse experiments
entailed relatively rapid deposition under waning flow.

315 Multi-pulsed Flow Deposition

316 Based on the interpretation of saline multi-pulsed flow experiments, Ho et al. (2018a, 317 2018b) suggested that multi-pulsed turbidites would persist up to the point of merging, with 318 normally-graded turbidites deposited thereafter. However, the data collected in this study 319 show only weak proximal development of multi-pulsed grading, expressed as two intervals 320 of inverse-to-normal grading in the d84 grainsize fraction at the most proximal measured 321 position (red trace in Fig. 8C, at 0.7m); otherwise normal grading patterns develop well 322 before the merging point (see section 3.4, above). The links between the longitudinal 323 variation of flow velocity structure, the grainsize of sediments falling from suspension in any 324 particular location and the resultant deposit grading profiles are unclear. An explanation is 325 therefore developed to account for the observed patterns of deposition; it assumes that 326 sediments aggrade progressively from overpassing flows (e.g., Choux & Druitt 2002; Kneller 327 & McCaffrey 2003; Amy et al. 2005).

Prior to the second release, it is thought that the first pulse developed vertical density stratification due to incipient deposition and entrainment of ambient fluid. Ambient water entrainment occurs both at the flow front and above the flow body (Hallworth et al. 1993; Sher & Woods 2015; Dorrell et al. 2016). Density stratification is also enhanced by particle sedimentation (Middleton & Hampton 1973; van de Berg et al. 2017). Therefore, a relatively-concentrated near-bed layer with a high proportion of faster-settling coarse sediments may develop, with more dilute flow above due to ambient water entrainment (e.g., Kneller & Buckee 2000; see also Stevenson 2014); the point of transition may not
correspond to the level of the velocity maximum. In the absence of near-bed flow data, it
cannot be determined if the basal layer became sufficiently dense such that grain-grain
interactions affected sediment deposition (e.g., Stevenson et al. 2014).

339 At proximal locations, the deposition of multi-pulsed turbidites is reflective of the 340 longitudinal variation in mean grain size of the overpassing flow immediately above the 341 depositional interface. Sediments comprising the near-bed layer of the first pulse are 342 deposited. At the depositional interface, slightly finer sediments are likely carried by the 343 pulse front and slightly coarser sediments by the body and the tail (e.g., Hand 1997, 344 McCaffrey et al. 2003; Baas et al. 2005; Fig. 7). Assuming that the response time-scale of 345 sediments in suspension is near-instantaneous (Dorrell & Hogg 2011), the vertical structure 346 of deposits attributed to the first pulse at any location would exhibit the classic inverse 347 graded base succeeded by an upward-fining profile. The head of the second pulse is 348 associated with a local increase in mean flow velocity (i.e., waxing flow; Figs. 5, 6). Coarse 349 material transported in the second pulse thus interacts with the relatively finer particles 350 composing the tail of the first flow (Dorrell et al. 2011, 2013). Coarser sediments within this 351 second pulse falling from suspension, either directly onto the bed, or through a vestigial 352 basal layer associated with the first pulse, will result in an upward-coarsening trend 353 principally expressed through variations within the coarsest sediments (e.g., via a measure 354 such as d84). Such deposition is followed by that of the fine sediment remnants of both 355 pulses. The proximal compound deposit will therefore show a multi-pulsed vertical grading 356 pattern (e.g., Fig. 8C, 0.7 m). The inverse graded intervals within a multi-pulsed turbidite 357 may arise either due to longitudinal coarsening within the second pulse, or due to the 358 grainsize difference between finer-grained sediments attributed to the first pulse and coarser sediments attributed to the second or due to a combined effect; the data do notreadily allow these possibilities to be discriminated.

361 Because the second pulse travels more quickly than the flow head (Ho et al. 2018a), 362 the time-period between its arrival and that of the head progressively reduces down the 363 flume; in addition this pulse is thought to rapidly deplete in coarser sediments due to 364 proximal deposition. Therefore both the difference in the grain size of suspended sediments 365 between successive pulses and the time for the depositional boundary to react to changing 366 flow conditions (see Dorrell & Hogg 2011) progressively reduce distally; jointly these effects 367 are thought to suppress any multi-pulsed signature in the deposit grading pattern. The 368 spatial scales over which coarse sediments in the second pulse are carried within the basal 369 layer cannot be deduced directly in this study, preventing estimation of the spatial 370 persistence of multi-pulsed turbidite deposition caused by flow surging. Consequently, if it is 371 applicable to turbidity currents, the scaling analysis conducted by Ho et al. (2018b) based on 372 data from saline flows only provides an upper limit on merging lengths; single-pulsed 373 turbidites may form before this point.

374 Methodological and Modelling Limitations

375 The development of single-pulsed turbidites prior to point of merging may result from the 376 experimental modelling approach. The proportion of coarse sediments in the initial pulses 377 of dense fluid was smaller than those of finer sediment classes (see Appendix A). Since the 378 inverse-to-normal grading of multi-pulsed turbidites appears to be expressed principally in 379 the relative distributions of coarser grained sediments (e.g., Fig. 8C, 0.7 m), the small 380 proportion of such sediments might contribute to the absence of discernible multi-pulsed 381 turbidites before the merging point. A contrary explanation is that the limit of coarse 382 sediment transport (and thus the development potential of multi-pulsed turbidites prior to the point of merging) may depend upon the presence of finer grained particles. This is because increasing the relative proportion of finer grainsizes is known to increase the distance of coarse sediment transport; finer sediments remain in suspension over longer times and thus sustain the associated flows (Gladstone et al. 1998, Gladstone & Woods 2000; Harris et al. 2002).

388 The focus of this contribution has been on the development of cycles of inverse to 389 normal grading within turbidites (e.g., Sumner et al. 2008; Ho et al. 2018a, 2018b). 390 However, this topic can be placed within a broader evaluation of the development of 391 variable grading patterns and their causes including the development of basal inverse 392 grading (e.g, Hand, 1997; Sumner et al. 2008) and of grainsize breaks (Kneller and McCaffrey 393 2003; Stevenson et al. 2014). Thus, patterns of repeated coarsening and fining produced in 394 annular flume experiments have been related to episodes of erosion and deposition within 395 slowly aggrading deposits associated with development of sedimentary laminae (Sumner et 396 al., 2008); as noted above, the inverse grading documented in the experiments reported 397 here is unlikely to have formed by this process. Stevenson et al. (2014) document a range of 398 examples of abrupt grainsize breaks within turbidites sampled along deposition transacts > 399 2000 km length in the Moroccan Turbidite System. Those related to deposition beneath 400 Newtonian flows are explained by flows waxing to bypass or bypassing due to changes 401 between capacity- vs. competence related deposition to explain the superposition of finer-402 grained over coarser-grained sediments (see also McCaffrey and Kneller, 2003; Kane et al. 403 2009). However, flow waxing alone is invoked to explain those cases in which inverse 404 grading is seen within the coarser-grained intervals. Erosion and bypassing may occur in 405 prototype environments during significant periods of a flow (e.g., Rimoldi et al. 1996; Sultan 406 et al. 2007; Stevenson et al. 2013; 2014); as well as causing grainsize breaks in their own right such processes may also affect the development of surge-related multi-pulsed
turbidites, which may be distorted and/or destroyed due to non-deposition or erosion. This
subject remains a topic for future study.

410 **CONCLUSIONS**

411 Experiments conducted to study the dynamics of single- and multi-pulsed turbidity currents 412 confirm that after an initial period of abruptly waxing velocity, the mean velocity of single-413 pulsed currents reduces monotonically in the waning phase, whereas that of multi-pulsed 414 flows transitions from waxing-waning cycles to monotonic reduction in their waning phase. 415 This pattern is similar to that observed in the dynamics of multi-pulsed saline flows (Ho et al. 416 2018a) and confirms that intra-flow velocity pulses are advected forwards, eventually 417 reaching the flow front at pulse merging points. The work further confirms that a minimum threshold separation time between the release of individual pulses is required if the 418 419 resulting flows are to exhibit multi-pulsed character. In the experimental scenario, this 420 minimum delay period corresponds to the time required for the backward-propagating 421 wave generated upon the collapse of the first pulse to reach the second lock gate. Pulse 422 delay periods less than the threshold interval result in the development of single-pulsed 423 flows.

Although the data support the inference of Ho et al. (2018a and b) that initiation signals may potentially be expressed through the development of multi-pulsed turbidites and that normally graded turbidites found beyond the final point of pulse merging cannot express such signals, the assumed correspondence between the merging point and the cessation of multi-pulsed turbidite deposition was not confirmed; the transition occurred well upstream. Therefore, if the scaling analysis derived for saline flows (e.g., Ho et al. 2018b) is used to predict pulse merging points in natural scale turbidity currents, it can provide only an upper limit to the distance over which multi-pulsed turbidites may be
developed. Whether or not multi-pulsed turbidites persist up to the merging point depends
upon the transport potential of coarser grains carried within pulses; the optimal grainsize
distribution to maximise this potential remains unknown.

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- 642 **Figure captions**:
- Figure 1 Experimental set-up. Note: i) aDvp/FBRM data were collected at x=1.7 m, 2.7 m
 and 3.7 m centred at midpoint of offset between the two probes, ii) sediments were
 sampled at x=0.7 m, 1.7 m, 2.7 m, 3.7 m and 4.7 m and iii) the back of the second
- 646 lockgate (i.e., right end of the flume) starts at 0.15 m position so the absolute
- 647 distances between sampling positions and source are x 0.15 (m).
- 648 **Figure 2** The evolution of single-pulsed flow (0 s delay time).
- 649 **Figure 3** The evolution of 2.5 s delay time flow.
- **Figure 4** The evolution of 8 s delay time flow.
- 651 Figure 5 aDvp data showing variation in velocity field of A) single-pulsed flows, B) 2.5 s
- delay time flows and C) 8 s delay time flows. Note that the experimental set-up in
- 653 which two laterally offset aDvp probes were deployed results in a stitching artefact
- 654 such that the flows arrived at the upper probe first, then at the lower one 2 s later.
- **Figure 6** Depth-averaged velocity of A) 0 s delay time flows, B) 2.5 s delay time flows and C)
- 656 8 s delay time flows. Note that effects of surface waves are indicated by the
- 657 fluctuation of data, especially during waning phases. However, the magnitudes of
- the waves are relatively small compared to the flow velocity (see e.g., Ho et al.
- 659 2018a).
- Figure 7 Real time particle size distribution at 2 cm height of A) single-pulsed flows, B) 2.5 s
 delay time flows and C) 8 s delay time flows. Note: the reduction in proportions of

- mean grainsize at 22-25 s, x=1.85 m for the 2.5 s delay time flow and that within 34-
- 663 46 s, x=1.85 m for 8 s delay time flow are interpreted as a result of technical glitch.
- 664 Figure 8 Vertical grading profiles of deposits of single-pulsed (2.5 s delay time) and multi-
- pulsed (8 s delay time) flows collected at 0.7 m, 1.7 m, 2.7 m, 3.7 m and 4.7 m. Notes: i)
- aDvp data were collected at 1.7, 2.7 and 3.7 m positions (Figs. 5 and 6), ii) Groups A, B and C
- 667 represent fine, medium and coarse fractions.
- 668 **Figure 9** Standard deviation of grain sizes vs depositional thickness.





T = 20 s





T = 30 s



T = 35 s



T = 40 s











- 15 s

- = 0 s

First pulse component









Second pulse component



T = 15 s







22

R

12

22

因







360

365

370

375

380

382

T = 25 s





410

T = 30 s

After point of merg



-

CAN I

210 205 200 195 190 185 180

1

-











DYNAMICS AND DEPOSITION OF SEDIMENT-BEARING MULTI-PULSED FLOWS AND GEOLOGICAL IMPLICATION

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Key words: multi-pulsed turbidites, pulsed turbidites, multi-pulsed flows, single-pulsed turbidites, sediment-bearing flows

Supplementary materials



Figure A-1 - Grain size distribution and grain shape data of sediments in the lockboxes used in the experiments.



Figure A-2 - Comparison between two data sets of grain size distribution analysed using the same control mixture of sediments; such control mixture is representative of the composition of sediments used in the lockboxes. Note: i) analysis using laser diffraction granulometry method, blue curve (by deploying Malvern 2000e), ii) analysis using FBRM measurement and inversion, red curve and iii) this plot indicates that the reliability of the inversion algorithm is acceptable.