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Coming to light: How effective are sediment gravity flows in removing fine suspended carbonate from reefs?

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Abstract:	<p>Coral reefs are hard calcified structures, mainly found in tropical water. They serve an important role as, for example, a food source, shelter and nursery for different organisms, and coastal protection. Reef-building organisms are susceptible to rapid changes in their environment under predicted climate-change scenarios. Anthropogenic climate change is widely accepted as the leading cause of rising ocean temperatures, seawater acidity and sedimentation rate, affecting a coral's productivity, health and skeletal strength. Storms and hurricanes can erode reefs, thereby increasing amounts of suspended sediment and consequently water turbidity. The removal of suspended sediment from the reef is vital for the health of reef producers; a natural process for this removal are sediment gravity flows (SGFs). A key factor that controls the ability of SGFs to transport sediment is cohesion, which determines the run-out distance of a flow through changes in rheological properties. This laboratory study examines the cohesive nature of SGFs laden with fine-grained CaCO₃. These gravity flows are compared with flows carrying non-cohesive, silt-sized, silica flour, weakly cohesive kaolinite clay, and strongly cohesive bentonite clay. The experimental results show that the mud-grade calcite flows behave more akin to the silica-flour flows by reaching maximum mobility at considerably higher volumetric suspended sediment concentrations than the kaolinite and bentonite flows. Fine CaCO₃ gravity flows can therefore be regarded as physically non-cohesive, and their high mobility may constitute an effective mechanism for removing suspended sediment from coral reefs, especially at locations where a slope gradient is present, such as at the reef front and forereef. However, biological cohesion, caused by 'sticky' extracellular polymer substances produced by micro-organisms, can render mud-grade calcite cohesive and SGFs less mobile. This study is therefore a first step towards a more comprehensive analysis of the efficiency of removal of suspended sediment from coral reefs.</p>



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27 in its rheological properties. This study examines the cohesive nature of sediment gravity
28 flows laden with fine-grained CaCO_3 . These gravity flows laden with mud-grade calcite are
29 compared with flows carrying non-cohesive, silt-sized, silica flour, weakly cohesive kaolinite
30 clay, and strongly cohesive bentonite clay, by means of laboratory experiments. The results
31 of these experiments show that the mud-grade calcite flows behave more akin to the silica-
32 flour flows by reaching maximum mobility at considerably higher volumetric suspended
33 sediment concentrations (47% for silica flour and 53% for CaCO_3) than the kaolinite and
34 bentonite flows (22% for kaolinite and 16% bentonite). Fine CaCO_3 gravity flows can therefore
35 be regarded as physically non-cohesive, and their high mobility may constitute an effective
36 mechanism for removing suspended sediment from coral reefs, especially at locations where
37 a slope gradient is present, such as at the reef front and forereef. However, biological
38 cohesion, caused by 'sticky' extracellular polymer substances produced by micro-organisms,
39 can render mud-grade calcite cohesive and sediment gravity flows less mobile. The present
40 study should therefore be seen as a first step towards a more comprehensive analysis of the
41 efficiency of removal of suspended sediment from coral reefs.

42

43 **KEYWORDS**

44 Mud-grade calcite, Sediment gravity flows, Cohesion, Laboratory experiments

45

46 **1 | INTRODUCTION**

47 Sediment gravity flows (SGFs) are amongst the most important sediment transport processes
48 on Earth, providing large quantities of sediment, carbon, nutrients and pollutants, such as
49 microplastics, to lakes, seas, and oceans (e.g., Kneller & Buckee, 2000; Postma, 2011; Talling,
50 2014). In the ocean, SGFs can cause considerable damage to underwater communication
51 cables and other deep-water engineering infrastructure (Talling et al., 2015). Although most
52 research on SGFs has focussed on siliciclastic sediment transport and environments, their
53 deposits are common also in modern and ancient carbonate environments (e.g., Austin et al.,
54 1986; Eberli, 1987; Eberli et al., 1997; Swart et al., 2000; Payros & Pujalte, 2008; Betzler et al.,
55 2017; Liu et al., 2023). Yet, process-based research of carbonate-laden gravity flows, and

56 comparisons with siliciclastic gravity flows, is relatively rare (e.g., Hodson & Alexander, 2010).
57 A recent paper by Slooman et al. (2023) summarised the present knowledge of the physics
58 of carbonate-sand laden SGFs and analysed the effect of carbonate particle shape and density
59 on their settling velocity in SGFs and their distribution in SGF deposits. Slooman et al. (2023)
60 concluded that “in addition to grain size and particle density, the irregular shape of skeletal
61 sediments exerts a significant control on the distribution of sand grains in calciturbidites”, but
62 their work did not include calciclastic, fine-grained sediment. Below, the term ‘mud-grade
63 calcite’ is used to describe this sediment in a purely granulometric sense, i.e., a mixture of silt
64 and clay-sized CaCO_3 particles, without reference to a specific physical, biological or chemical
65 origin (e.g., Hubbard et al., 1990).

66 Fine-grained sediment, including mud-grade calcite, can be cohesive, ‘sticky’, which has wide-
67 ranging implications for the dynamic behaviour, i.e., ‘mobility’, of SGFs (e.g., Marr et al., 2001,
68 Mohrig & Marr, 2003; Sumner et al., 2009; Baas et al., 2009, 2011; Baker et al., 2017), as
69 cohesion works against the gravity-induced principle that flow velocity increases as
70 suspended sediment concentration increases. Particle attraction by cohesion in SGFs can have
71 physical and biological origins (Craig et al., 2020) and these cohesive forces work against
72 turbulent forces to decrease the mobility of SGFs (Baas et al., 2009, 2011). In siliciclastic-clay
73 laden flows, the decrease in mobility may start at a volumetric clay concentration of c. 10%
74 (Baker et al., 2017), although this threshold varies with flow velocity, i.e., turbulence intensity;
75 stronger turbulence leads to more breakage of electrostatic bonds between fine particles.
76 Mud-grade calcite consists of fine-grained calcium carbonate that can be entrained, in
77 conjunction with coarser sediment, into the water column in large quantities on carbonate
78 platforms (including reefs) during storms and subaqueous slope failures. This resuspended
79 sediment may then be shed offshore by SGFs (Haak & Schlager, 1989; Reijmer et al., 1992,
80 2012; and further references in Slooman et al., 2023). The origin of mud-grade calcite can be
81 biological, chemical, and detrital (Hubbard, 1990; MacDonald & Perry, 2003; Perry et al.,
82 2015; Russ et al., 2015; Trower et al., 2019). The production of mud-grade calcite is a common
83 process on carbonate platforms. However, it is particularly important for unhealthy, brittle
84 reefs subjected to environmental stress, such as coral bleaching, because their weakened
85 skeleton renders these reefs more susceptible to: (a) physical erosion and subsequent
86 production of mud by abrasion of eroded sand and rubble (Trower et al., 2019), and (b)

87 biological erosion and production of mud by scrapers and excavators, e.g., parrot fish and
88 urchins (Salter et al., 2012; Perry et al., 2015; Russ et al., 2015), cyanobacterial infestation,
89 post-mortem disintegration of calcareous algae, and micro and macroborers, e.g., sponges
90 (MacDonald & Perry, 2003; Perry et al., 2015).

91 Generally, the presence of large volumes of suspended mud is detrimental to carbonate
92 producers and, thus, to sediment production and reef growth (e.g., Rogers & Ramos-
93 Scharrón, 2022; Tuttle & Donahue, 2022). Carbonate production is highest in sessile benthic
94 organisms precipitating skeletal material in association with photosynthesis. This process is
95 optimum in shallow clear waters within the uppermost few metres of the photic zone. The
96 presence of mud in the water column reduces the depth of the photic zone and, thus, reduces
97 the incident light at the sea floor — a process akin to an increase in water depth. Turbidity
98 can have a major impact on gross carbonate production, taphonomy and sediment
99 production of reefs (e.g., Mallela & Perry, 2006). Where mud settles onto the reef surface,
100 carbonate producers may be stressed, or even killed, through ingestion or smothering (Lokier
101 et al., 2009; Lokier, 2023).

102 The aim of this paper is to determine, at first order, how effective SGFs are, in addition to
103 wind, waves, and tides (e.g., Lopez-Gamundi et al., 2024), in shedding fine suspended CaCO_3
104 sediment off reefs, considering that removal of suspended sediment from the water column
105 above reefs is needed to clear turbid water and aid the maintenance of reef health (e.g., Jones
106 et al., 2020). Experimental research was used to compare the head velocity, run-out distance,
107 and deposit shape of flows laden with mud-grade calcite (crushed limestone) with non-
108 cohesive siliciclastic silt flows and cohesive siliciclastic clay flows. This comparison aims to
109 derive a descriptive measure of the degree of cohesion of SGFs laden with mud-grade calcite.
110 The hypothesis is that, if fine CaCO_3 flows are non-cohesive, the low settling velocity of the
111 mud-grade calcite renders these flows highly mobile and well able to remove suspended
112 sediment from reefs after storms. The specific objectives of this research are therefore:

- 113 1. to determine if SGFs laden with mud-grade calcite (crushed limestone) are physically
114 cohesive or non-cohesive;
- 115 2. to quantify changes in mobility of mud-grade calcite SGFs and deposit shape as a function
116 of suspended CaCO_3 concentration;

- 117 3. to discuss differences between healthy and unhealthy, brittle reefs in the efficiency of
118 CaCO_3 -laden flows to clean turbid water, especially after storms;
119 4. to consider the potential effect of biological cohesion and particle shape and density on
120 the mobility of SGFs laden with mud-grade calcite in view of future research.

121

122 **2 | BACKGROUND AND RATIONALE**

123 **2.1 | Coral reefs**

124 Coral reefs are amongst the largest and most complex ecosystems on Earth, primarily found
125 in warm waters in the tropics (Spalding, 2001). Most reef-forming scleractinian corals host
126 symbiotic dinoflagellate zooxanthellae that use light to provide nutrients to the coral
127 (Berkelmans & van Oppen, 2006). Millions of species worldwide call reefs their home
128 (Sheppard et al., 2017) and an estimated 6 million people around the globe are dependent on
129 coral reefs (Cinner, 2014). Reefs supply job opportunities to local communities and they
130 provide a food source and recreational opportunities, such as diving and eco-tourism
131 (Costanza et al., 2014). Reefs also support coastal communities by providing protection
132 against coastal hazards. As such, coral reefs act like sandbars and barrier islands by dispersing
133 wave energy from storms and hurricanes (Spalding et al., 2014).

134 Because of the delicate relationship with zooxanthellae, coral reefs are sensitive to outside
135 stressors, such as heat, acidification, and sedimentation. Coral species, in particular, are
136 susceptible to change. If the external stressors become too strong, the zooxanthellae are
137 expelled from the coral, leaving them colourless (bleached). The world's oceans have been
138 warming since the rise of the industrial revolution, in parallel with the increase of atmospheric
139 carbon. Carbon dioxide gas traps heat close to the Earth surface, with the oceans serving as a
140 heat sink (Stocker et al., 2013). The increased seawater temperature negatively affects the
141 health of coral reefs, which can only thrive within a narrow water temperature range (Wilson,
142 2012). A direct consequence of rising oceanic CO_2 levels is ocean acidification. This happens
143 when seawater and CO_2 mix to make CO_3^{2-} (carbonate), HCO_3^- (bicarbonate) and
144 H^+ (hydrogen), which lowers the pH. As a result of ocean acidification, corals cannot produce
145 calcium carbonate as easily (e.g., Langdon & Atkinson, 2005). Reefs that have undergone
146 bleaching because of rising seawater temperature and possibly also ocean acidification

147 (Anthony et al., 2008) are more delicate than healthy reefs. In the period between 1980 and
148 2016, the years 1998, 2005, 2010, and 2016 had particularly high numbers of bleaching events
149 around the world (Hughes et al., 2018). Without a strong calcified outer layer, a coral is more
150 susceptible to physical and biological erosion (MacDonald & Perry, 2003; Perry et al., 2015;
151 Russ et al., 2015; Trower et al., 2019). Reefs in the tropics suffer regular high energy events,
152 as hurricane-generated waves and storm surges are common at these latitudes. During these
153 events, corals as far down as 20 m can be affected, with certain growth forms, such as
154 branching corals, being particularly susceptible (Scoffin, 1993). It is therefore hypothesised
155 that an unhealthy, brittle reef produces more suspended sediment, including mud-grade
156 calcite via abrasion of sand and gravel (Trower et al., 2019), during a storm or hurricane than
157 a stronger, more calcified, healthy reef. The problem is compounded by the fact that reefs
158 that have been affected by natural or anthropogenic disturbances exhibit slower coral
159 recovery rates under higher turbidity conditions (Evans et al., 2020). Moreover,
160 anthropogenic eutrophication causes a change in the balance of coral versus coralline algae
161 within the reefs (e.g., Chazottes et al., 2008), which further exacerbates the production of
162 large amounts of mud-grade carbonate sediment by, in particular, biological erosion.

163 The amount of sediment input to reefs from anthropogenic sources, such as remobilisation
164 by fishing and dredging, has increased substantially (Brodie & Pearson, 2016). High levels of
165 suspended sediment above and around coral reefs make the water more turbid, reducing the
166 light penetration to the corals and hindering photosynthesis and zooxanthellae productivity
167 (Rogers, 1990). Sediment settling on coral tissue causes further shading and smothering.
168 Healthy corals can actively remove small amounts of sediment from their tissues via ciliary
169 activity, hydrostatic expansion, tentacle movements, and mucus production (Brunner, 2021),
170 but unhealthy corals are less able to do so. Shading and smothering contribute to a further
171 decrease in the productivity of the photosynthesising zooxanthellae; this is another major
172 cause of coral bleaching (Erftemeijer et al., 2012). Where smothering is significant, corals, and
173 other sessile benthic carbonate producers, will be killed through anoxia or tissue narcosis
174 (references in Lokier, 2023). Even small amounts of smothering may kill carbonate producers,
175 as an inability to feed results in starvation. Calcification rates are three times higher in light
176 conditions than in dark conditions, and recent studies have suggested that calcification is
177 dark-repressed rather than light-enhanced (e.g., Venn et al., 2019). Thus, a coral reef in

178 seawater with high amounts of suspended sediment calcifies less (Gattuso, 1999). This lower
179 calcification rate results in the construction of a weaker skeleton and, thus, higher
180 vulnerability of the reef to biological erosion (MacDonald & Perry, 2003; Perry et al., 2015;
181 Russ et al., 2015) and mechanical breakdown during storms (Crook et al., 2013). In turn, more
182 suspended sediment needs to be transported away from the reef after storm events to ensure
183 coral productivity and health.

184

185 **2.2 | Sediment gravity flows**

186 Sediment gravity flows (SGFs) are known to shed suspended sediment off reefs into deeper
187 water (Haak & Schlager, 1989; Reijmer et al., 1992, 2012; and further references in Slooman
188 et al., 2023), but SGFs vary significantly in their efficiency of transporting sediment, i.e., in
189 flow mobility. The controls on the mobility of SGFs can be summarised by four main factors:
190 (1) flow type, which can be laminar, transitional, or turbulent; (2) flow behaviour, which can
191 be cohesive or non-cohesive; (3) excess density of the flow, relative to the ambient water;
192 and (4) substrate slope gradient (Talling et al., 2012). The present paper focusses on cohesion
193 and excess density, here expressed as volumetric sediment concentration. Depending on flow
194 type and rheology, SGFs can behave as a fluid or plastic. Examples of fluidal flows used in this
195 paper are low-density and high-density turbidity currents (Baker et al., 2017). Mud flows and
196 slides, also used in this paper, are examples of plastic flow (Baker et al., 2017).

197 Following the definitions of Baker et al. (2017), low-density turbidity currents are fully
198 turbulent, i.e., well-mixed flows without an internal density interface (Table 1; Baker et al.,
199 2017). High-density turbidity currents (Baker et al., 2017) have two distinct layers: a low-
200 density, fully turbulent cloud of suspended sediment in the upper part separated by a density
201 interface from a high-density layer with reduced turbulence in the lower part of the flow
202 (Table 1). Mud flows are defined as high-concentration, laminar SGFs without significant
203 internal turbulence, in which a cohesive clay gel provides grain support by matrix strength
204 (Middleton & Hampton, 1973; Baker et al., 2017). Mud flows may have a dilute top, caused
205 by minor mixing with the ambient water. A slide is a coherent mass flow without significant
206 internal deformation, formed at the highest suspended sediment concentrations (Table 1;
207 Baker et al., 2017).

208 **2.3 | Cohesion**

209 SGFs can be subdivided in non-cohesive, dominantly fluidal, flow types and cohesive,
210 dominantly plastic, flow types. Cohesive SGFs are more complex than non-cohesive SGFs,
211 because of the ability of clay particles to form aggregates (floccules) and gels (e.g., Mehta et
212 al., 1989). The presence of floccules and gels increases the viscosity and yield strength and
213 modulates the turbulence maintaining the flow (Baas & Best, 2002). Floccule size generally
214 increases as bulk suspended-clay concentration increases (Dyer & Manning, 1999) until a
215 gelling point is reached, at which a volume-filling network of clay particle bonds in the liquid,
216 i.e., a gel, establishes.

217 Settling of clay particles is dependent on the concentration — and less so on the size — of
218 individual clay particles, if the settling is controlled by the aggregation and gelling processes
219 (Dyer & Manning, 1999). In low-concentration suspensions, in which flocs are small, the
220 settling velocity and concentration are independent of each other. However, in high-
221 concentration suspensions, particles are more likely to form large flocs, which usually have a
222 greater submerged weight, and therefore a higher settling velocity (Dyer & Manning, 1999).
223 Clay gelling inhibits the turbulence of the flow through increased viscosity (Baker et al., 2017).
224 Flows that behave as a gel tend to deposit 'en masse'. This bulk settling process involves a
225 positive feedback mechanism, 'cohesive freezing' (Mulder & Alexander, 2001). Cohesive
226 freezing typically follows a reduction in the head velocity of the flow, which decreases
227 turbulent forces, allowing the clay minerals to form a greater number of electrostatic bonds,
228 in turn increasing cohesive strength. This then further reduces the turbulence and results in
229 a rapid further reduction in the head velocity of the flow. This deceleration process repeats
230 itself until the flow swiftly comes to a halt. The equivalent process in non-cohesive, usually
231 silt-laden, SGFs is 'frictional freezing'. Frictional freezing takes place at considerably higher
232 sediment concentrations than cohesive freezing, because non-cohesive particles do not form
233 gels (Baker et al., 2017).

234 **2.4 | Research approach**

235 In order to estimate how effectively fine suspended CaCO₃ sediment can be transported by
236 SGFs, lock-exchange experiments were conducted with mud-grade calcite gravity flows. The
237 experiments comprised a full range of initial suspended sediment concentrations, covering

238 low-density and high-density turbidity currents, mud flows, and slides (sensu Baker et al.,
239 2017). The observation that flows carrying fine non-cohesive siliciclastic particles (silica flour
240 in Table 2) are highly mobile up to volumetric concentrations of 52% and equivalent cohesive
241 SGFs lose mobility at much lower concentrations, e.g., at 20% for bentonite clay (Table 2;
242 Baker et al., 2017), allows us to estimate the cohesive properties of the mud-grade calcite
243 flows through comparison of head velocity, run-out distance, and deposit shape, following
244 procedures used by Craig et al. (2020), Sobocinska & Baas (2022) and Baker & Baas (2023) for
245 siliciclastic sediment. In turn, this information is used to discuss how effective mud-grade
246 calcite SGFs can be in cleaning turbid water above reefs, primarily based on the degree of
247 cohesion, but also taking other controls on flow mobility, such as biological cohesion, into
248 consideration.

249

250 **3 | METHODS AND MATERIALS**

251 Fifteen lock-exchange experiments were conducted in the Hydrodynamics Laboratory of
252 Bangor University (NW Wales, U.K.) between October 2022 and February 2023. The lock-
253 exchange tank is 5 m long, 0.2 m wide, and 0.5 m deep (Figure 1). It is made up of two sections:
254 a 0.31-m long reservoir separated from the 4.69-m long main body by a lock gate. The slope
255 of the tank was set to 0° in all experiments to allow direct comparison with the siliciclastic
256 flows studied by Baker et al. (2017), to minimize the number of variables, and to achieve a
257 minimum requirement for mud removal, as slopes promote flow and favour turbulent driving
258 forces over mobility-reducing cohesive forces. For each experiment, the reservoir was filled
259 with a mixture of seawater and fine-grained calcium carbonate particles to a depth of 0.35 m
260 (Figure 1). The remainder of the tank was filled simultaneously with seawater to the same
261 level as in the reservoir. The seawater was sourced from the Menai Strait (NW Wales, U.K.)
262 and filtered to remove suspended particles before application. The salinity and temperature
263 of the seawater were 35 psu and c. 15°C, respectively. As a first-order approximation of
264 natural mud-grade calcite, the calcium carbonate used in the experiments consists of crushed
265 limestone (calcite) without significant intraparticle porosity, manufactured by Omya® (C.A.S.
266 number 1317-65-3) and supplied under the name “Calcium Carbonate Powder” by Elixir
267 Garden Supplies in the U.K. The size distribution of the mud-grade calcite was measured using
268 a Microtrac Sync laser particle sizer at the School of Ocean Sciences, Bangor University. The

269 mud-grade calcite is a very poorly sorted sandy mud with a median size of 0.009 mm (6.9 ϕ :
270 fine silt) and a sorting coefficient of 2.466 (Folk & Ward, 1957). Figure 2 shows two main
271 modal sizes at 0.0025 mm (8.6 ϕ : clay) and 0.060 mm (4.1 ϕ : coarse silt). The volumetric
272 concentration of CaCO₃ in the flows ranged from 1% to 59%.

273 A consistent method was used to prepare each mixture of seawater and mud-grade calcite to
274 account for any settling and time-dependent rheological behaviour. Volumetric suspended
275 sediment concentrations were determined from the density, ρ , and required mass of CaCO₃
276 and seawater, with $\rho_{\text{mud-grade calcite}} = 2710 \text{ kg m}^{-3}$ and $\rho_{\text{seawater}} = 1027 \text{ kg m}^{-3}$. The total volume
277 of the mixture was 0.02446 m³. This was sufficient to fill the reservoir to a depth of 0.4 m,
278 thus allowing for some loss of the mixture during preparation. Dry CaCO₃ and seawater were
279 mixed for 10 minutes in a concrete mixer. Thereafter, the suspension was decanted in a
280 container and the walls of the mixer were scraped down to ensure that as little as possible of
281 the mixture was left in the mixer. The suspension was then mixed with a handheld mixer for
282 a further 3 minutes to make sure the mixture was free of lumps. Subsequently, the mixture
283 was transferred to the reservoir whilst the main body of the tank filled with seawater, to avoid
284 leakage because of pressure differences between both sides of the lock gate. Immediately
285 before lifting the gate and starting an experiment, the mixture in the reservoir was
286 homogenised for 60 s with the handheld mixer. A HD video camera, attached to runners on
287 top of the tank, tracked the front of the flow along the tank. The video recordings were used
288 to describe and classify the SGFs (cf., Baker et al., 2017) and determine the mean velocity of
289 the head of the flow at each 0.1 m distance along the flow path, as well as the run-out distance
290 of flows that did not reach the end of the tank. Deposit thicknesses were measured with
291 electronic callipers and rulers, but only for flows that did not reflect off the end wall, as these
292 reflections disturbed the deposits. Maximum head velocity of the flows along the tank is used
293 throughout this paper to allow a comparison with previous work on siliciclastic silt and clay
294 flows.

295

296 **4 | RESULTS**

297 The experimental data for the mud-grade calcite experiments are summarised in Table 2,
298 which also shows the experimental results of Baker et al. (2017) for kaolinite clay, bentonite

299 clay, and silica flour that were conducted using the same method. Figure 3 depicts the heads
300 of selected mud-grade calcite flows. Figure 4 shows changes in head velocity with distance
301 along the tank for all flows, and Figure 5 summarises changes in deposit thickness with
302 distance along the tank.

303 **4.1 | Visual observations**

304 The videos reveal that the 1% to 45% mud-grade calcite flows were all fully turbulent between
305 base and top (Figure 3A, B) and had a semi-elliptically shaped head and distinct Kelvin-
306 Helmholtz instabilities at their upper boundary in vertical cross-section parallel to the flow
307 direction. These flows kept their forward momentum to the end of the tank, suggesting that
308 the turbulence in these flows was able to outcompete the particle settling and kept most
309 particles in suspension until the flows reflected off the end wall. These properties match the
310 low-density turbidity current type of Baker et al. (2017) (Table 1).

311 The flows laden with 50%, 53% and 55% mud-grade calcite had two distinct parts separated
312 by a density interface (dashed white line in Figure 3C, D). The upper part of these flows had a
313 relatively light colour and mixed freely with the ambient seawater, whereas the lower part of
314 these flows was darker, denser, and undisturbed by the seawater (Figure 3C, D). The flow
315 front was more circular in vertical cross-section parallel to the flow direction than for the low-
316 density turbidity currents. The flows laden with 50%, 53% and 55% mud-grade calcite are
317 classified as high-density turbidity currents (cf., Baker et al., 2017; Table 1).

318 The flow laden with 58% mud-grade calcite had a characteristic lip at the top of the head
319 (white arrow in Figure 3E), The flow lacked internal mixing, and minor mixing with the ambient
320 water resulted in a dilute suspension cloud near the top of the flow. The head of the 58% flow
321 had a pointed shape and was lifted off the floor of the tank by incursion of seawater
322 underneath the base of the flow, i.e., the flow hydroplaned. These characteristics match the
323 mud-flow type of Baker et al. (2017).

324 The flow laden with 59% mud-grade calcite was wedge-shaped and it lacked internal
325 deformation. Mixing with the ambient seawater was negligible. The flow mobility was low
326 and most of the sediment was deposited close to the lock gate (Fig. 5). This flow is classified
327 as a slide (cf., Baker et al., 2017).

328 4.2 | Head velocity

329 Figure 4 shows how the head velocity of each mud-grade calcite flow changed with increasing
330 distance, x , from the lock gate. The initial head velocity, at $x = 0.15$ m, increased from 0.11 m
331 s^{-1} for the 1% flow to 0.63 m s^{-1} for the 30% flow (Figure 4A) and then to 0.83 m s^{-1} for the
332 45% flow (Figure 4B). As these low-density turbidity currents travelled along the tank, their
333 head velocity decreased to 0.053 m s^{-1} for the 1% flow, 0.39 m s^{-1} for the 30% flow (Figure
334 4A), and 0.46 m s^{-1} for the 45% flow (Figure 4B). All $\leq 45\%$ flows reflected off the end of the
335 tank, so they had a minimum run-out distance of 4.69 m.

336 In contrast to the low-density turbidity currents, the initial head velocity decreased as the
337 concentration of mud-grade calcite was increased from 50% to 59%: from 0.80 m s^{-1} for the
338 high-density turbidity current laden with 50% mud-grade calcite via 0.55 m s^{-1} for the mud
339 flow carrying 58% mud-grade calcite to 0.44 m s^{-1} for the slide laden with 59% mud-grade
340 calcite (Figure 4B). The 50% high-density turbidity current decelerated quicker than the low-
341 density turbidity currents near the end of tank but still maintained a head velocity of 0.35 m
342 s^{-1} close to the end wall. The 53% and 55% high-density turbidity currents, 58% mud-grade
343 calcite, and 59% slide stopped before reaching the end of the tank and did so progressively
344 closer to the lock gate (Figure 4B). These flows therefore had measurable run-out distances,
345 decreasing from 3.75 m to 0.75 m, as the concentration of mud-grade calcite was increased
346 (Table 2).

347 4.3 | Deposit properties

348 Figure 5 shows the deposits of all mud-grade calcite flows that had a measurable run-out
349 distance. The length of the deposits decreased, and their maximum thickness increased, as
350 concentrations of mud-grade calcite increased from 53% to 59%. The 53% high-density
351 turbidity current produced a relatively thin deposit with a length of 3.75 m, whereas the 59%
352 slide produced a thick and short deposit that extended into the tank by only 0.75 m. The
353 deposit shape of the high-density turbidity currents was different from that of the mud flow
354 and slide. The high-density turbidity current deposits thinned rapidly in the first metre, after
355 which the thickness was approximately constant for up to 3 m. The deposits then terminated
356 abruptly. The mud flow and slide deposits are characterised by more linear and more rapid
357 thinning than the high-density turbidity current deposits.

358

359 **5 | DISCUSSION**360 **5.1 | Is mud-grade calcite cohesive?**

361 Figure 6 depicts the maximum head velocity of the experimental flows as a function of
362 concentration of mud-grade calcite, and compares these with the strongly cohesive bentonite
363 clay, weakly cohesive kaolinite clay, and non-cohesive silica flour flows of Baker et al. (2017).
364 The maximum head velocity of the mud-grade calcite flows gradually increased, as the initial
365 suspended sediment concentration was increased from 1% to 45%, because increasing the
366 concentration of CaCO_3 increased the density contrast between the flow and the ambient
367 fluid; this excess density, together with turbulence, are the drivers of these low-density
368 turbidity currents. Despite the higher excess density in the mud-grade calcite laden high-
369 density turbidity currents, mud flow, and slide, the maximum head velocity decreased rapidly
370 as the sediment concentration was increased from 50% to 59% (Figure 6).

371 The shape of the maximum head velocity curve for mud-grade calcite matches that of
372 bentonite, kaolinite, and silica flour, but the mud-grade calcite curve is closest in terms of
373 maximum mobility, i.e., peak maximum head velocity, to the silica flour curve (Figure 6). This
374 peak is at 45% for mud-grade calcite and at 47% for silica flour, whereas the peaks for
375 bentonite and kaolinite are at 16% and 22%, respectively. As silica flour is non-cohesive, and
376 kaolinite and bentonite are cohesive (Baker et al., 2017), this suggests that the mud-grade
377 calcite flows behaved in a non-cohesive manner and can reach significantly higher mobilities
378 at higher concentrations than cohesive clay flows (Figure 6). The decrease in maximum head
379 velocity between 50% and 59% mud-grade calcite therefore most likely results from
380 attenuation of turbulence by frictional forces between the CaCO_3 particles within the flow,
381 rather than cohesive forces (which do not require particles to 'rub' against each other). The
382 fact that these concentrations are close to the random packing density of spheres in deposits
383 of 60% (loose random packing) to 64% (close random packing), when a pervasive network of
384 particle contacts is present and thus the frictional strength is highest, supports this
385 interpretation. The inference that the mud-grade calcite SGFs were non-cohesive, behaving
386 in a similar way to the non-cohesive silica-flour SGFs of Baker et al. (2017), is supported
387 further by similar trends in run-out distance (Figure 7) and deposit shape (Figure 8). The

388 bentonite and kaolinite clay flows started to run out and change deposit shape at much lower
389 concentrations than the silica-flour and mud-grade calcite flows (Figure 7).

390 Figure 6 reveals also that the mud-grade calcite flows were more mobile than the silica-flour
391 flows at concentrations above c. 30%. The mud-grade calcite flows reached a higher peak
392 maximum head velocity than the silica-flour flows (0.85 m s^{-1} versus 0.75 m s^{-1}) and frictional
393 forces slowed down the silica-flour flows at lower concentrations than the mud-grade calcite
394 flows. Moreover, matching run-out distances and deposit shapes are associated with higher
395 mud-grade calcite than silica-flour concentrations in high-density turbidity currents, mud
396 flows, and slides (Figure 7). This confirms that the high-concentration, turbulence-attenuated,
397 mud-grade calcite flows were more mobile than the silica-flour flows.

398 The comparison with Baker et al. (2017) in Figures 6–8 shows that the mud-grade calcite flows
399 were non-cohesive, yet somewhat more mobile than non-cohesive silica-flour flows under
400 turbulence-attenuated conditions. Although silica flour was deemed to be non-cohesive by
401 Parker (1987), Pashley & Karaman (2004) suggested that silica-flour particles have weak
402 negative surface charges. Silica flour may therefore be weakly cohesive — but considerably
403 weaker than kaolinite — possibly explaining the lower mobility of silica-flour laden high-
404 density turbidity currents, mud flows and slides compared to the equivalent mud-grade
405 calcite flow types. However, this inferred higher mobility of mud-grade calcite flows may be
406 partly counteracted by the presence of weak surface charges of CaCO_3 particles in electrolytic
407 solutions, such as seawater (Eriksson et al., 2007). Alternative explanations for the difference
408 in mobility between the high-concentration silica-flour and mud-grade calcite SGFs are
409 differences in median particle size (0.018 mm and 0.009 mm, respectively), particle size
410 distribution (poorly sorted and very poorly sorted, respectively) and particle shape (e.g.,
411 Slooman et al., 2023). Further research is needed to determine the effect of these
412 parameters on differences in flow mobility for siliciclastic and calciclastic sediment, especially
413 in dense, turbulence-modulated flows.

414 **5.2 | Wider implications**

415 Our laboratory experiments provide a fundamental physical understanding of the dynamics
416 of SGFs that carry fine-grained CaCO_3 . The experimental data suggest that these flows are
417 highly mobile up to concentrations that approach the packing density of deposits, because

418 mud-grade calcite is physically non-cohesive and frictional forces are needed to reduce flow
419 mobility. Since the experiments isolated a single parameter, physical cohesion, a detailed
420 comparison with dynamically more complex natural SGFs on coral reefs is not possible yet.
421 Natural flows can be faster than the SGFs simulated herein, in which case the changes in flow
422 type, e.g., from low-density to high-density turbidity current, should occur at even higher
423 suspended sediment concentrations than found in this study. It is therefore anticipated that,
424 purely from the perspective of the lack of physical cohesion, SGFs laden with mud-grade
425 calcite on coral reefs are as effective in transporting suspended sediment as in the
426 experiments. This includes sediment eroded and resuspended by storms and hurricanes and
427 sediment made available by slope failures on oversteepened reef fronts and forereefs. The
428 latter process is facilitated by the usually steep seaward slope gradient of coral reefs. Like in
429 non-carbonate environments, relatively low-concentration turbidity currents of high mobility
430 are more likely to occur than hyperconcentrated (more than 50% by volume of suspended
431 sediment) turbulence-suppressed mud flows and slides of low mobility on and around coral
432 reefs. However, there are conditions in which low-mobility flows might form. Natural SGFs
433 can be highly stratified, with suspended sediment concentrations significantly greater near
434 the bottom of the flow than near the top, e.g., for siliciclastic flows in the Congo Canyon
435 (Azpiroz-Zabala et al., 2017), which may take equivalent calciclastic SGFs on coral reefs into
436 the non-turbulent, frictional regime near the seabed. Moreover, failure of unstable slopes —
437 particularly involving ‘en masse’ erosion by, for example, delamination (Eggenhuisen et al.,
438 2011) — may initiate mud flows or slides. Notwithstanding these conditions, the lack of
439 physical cohesion should promote the transport of suspended fine-grained CaCO_3 away from
440 reefs by SGFs and thus the efficiency of cleansing turbid water after storms, so more light is
441 available for photosynthesis. This removal of suspended sediment is likely to be even more
442 effective above unhealthy reefs than above healthy reefs, because the increased volume of
443 biologically produced mud-grade calcite on unhealthy, brittle reefs (MacDonald & Perry,
444 2003; Perry et al., 2015; Russ et al., 2015), as well as the greater potential for sediment
445 erosion during storms, are expected to increase the suspended sediment concentration and
446 thus the excess density and mobility of SGFs.

447 However, physical cohesion is not the only parameter that controls the mobility of CaCO_3 -
448 laden SGFs. Biological cohesion associated with ‘sticky’ extracellular polymeric substances

449 (EPS) produced by microphytobenthos, bacteria and other micro-organisms, has been found
450 to reduce the mobility of SGFs at concentrations that are several orders of magnitude lower
451 than for physically cohesive, siliciclastic clay (Craig et al., 2020; Sobocinska & Baas, 2022).
452 Coral reefs are characterised by a large species richness and diversity and carbonate grains
453 coated in organic matter are common (e.g., Schieber et al., 2013). It is therefore likely that
454 EPS hinder the removal of suspended sediment by SGFs from reefs by increasing the cohesive
455 forces and attenuating the turbulent driving forces, especially in high-density turbidity
456 currents. On unhealthy reefs, microbial films and algae grow rapidly, outcompeting corals for
457 space (Tanner, 1995; Lirman, 2001; Barott et al., 2011), and producing large volumes of EPS.
458 This is postulated to further reduce the mobility of SGFs above and around unhealthy reefs
459 and thus reduce their ability to transport suspended sediment away from reefs compared to
460 healthy reefs. This reduced mobility on unhealthy reefs would work against the increased
461 mobility by the lack of physical cohesion, inferred above. Despite the conceivable reduction
462 in SGF mobility by biological cohesion, Hubbard (1986) showed that 1/3 to 1/2 of the annual
463 offshore sediment flux can be reached during merely two weeks of stormy weather. This
464 supports the strong influence of physical conditions on offshore sediment transport in
465 carbonate environments.

466 In addition to biological cohesion, particle shape and density also need to be considered in
467 assessing the mobility of CaCO₃-laden SGFs and their ability to clean turbid water (de Kruijf et
468 al., 2021; Bian et al., 2023). The mud-grade calcite used in the present experiments is not ideal
469 for studying these parameters, as it consists of finely powdered limestone that is suitable for
470 understanding the basic physical properties of mud-grade calcite SGFs, but it may not
471 represent the perceived compositional and textural variability of natural flows. Although the
472 density of CaCO₃ is comparable to that of quartz-rich siliciclastic sediment, the true density of
473 carbonate particles in natural environments is controlled by the internal porosity of bioclasts;
474 most bioclasts have a density below 2710 kg m⁻³. The shape of bioclasts is also more variable
475 than the shape of siliciclastic particles. Whereas siliciclastic particles usually approach a
476 spherical shape, the shape of bioclastic particles ranges from spherical for ooids to highly
477 irregular, depending on the shape of shells, skeletons, and other hard parts of calcifying
478 organisms, as well as fragments thereof (de Kruijf et al. (2021). Moreover, mud to silt-grade
479 carbonate produced in tropical reef environments is excreted by fish (Salter et al., 2012) and

480 may have a range of shapes as well as disaggregation potential (Perry et al., 2011). Based on
481 detailed laboratory experiments, Slooman et al. (2023) showed that natural non-spheroidal
482 skeletal carbonate sand generally has a lower settling velocity than spheroidal sand. This
483 implies that SGFs laden with non-spherical carbonate sand have a higher mobility than SGFs
484 with spherical sand, especially if the sand particles are porous. However, further research is
485 needed to verify if the results of Slooman et al. (2023) extend to SGFs laden with fine-grained,
486 clay and silt-sized, CaCO_3 .

487 The benefits of the perceived highly mobile nature of SGFs laden with mud-grade calcite may
488 extend beyond the cleansing of turbid water above shallow-water reefs that depend primarily
489 on photosynthesis. Deep-water reefs, including reefs in canyons, exist in the mesophotic zone
490 (30-150 m) (Lesser et al., 2009), where removing suspended sediment is not as vital as for
491 shallow-water reefs. Deep-water reefs rely less on sunlight for photosynthesis and more on
492 nutrient supply via heterotrophy rather than autotrophy (Mass et al., 2007). Hence, the high
493 mobility of mud-grade calcite SGFs makes them effective as export systems of sediment from
494 shallow-water reefs, and also as import systems of nutrients to deep-water reefs. Given the
495 recently discovered common occurrence of SGFs (e.g., Azpiroz-Zabala et al., 2017) and other
496 types of currents, such as tidal currents, in canyons, this process of nutrient supply to deep-
497 water reefs may be more important than realised up to now, and therefore add to better
498 known nutrient sources of pelagic and deep-water bottom-current origin.

499

500 **6 | CONCLUSIONS**

501 The present experimental research reveals that SGFs laden with mud-grade calcite are non-
502 cohesive and behave in a similar way to SGFs laden with non-cohesive siliciclastic fine silt.
503 Both flow types remain fully turbulent and highly mobile up to concentrations that approach
504 that of randomly packed deposits, reflected in similar maximum head velocity curves and
505 suspended-sediment-concentration controlled run-out distances and deposit thicknesses.
506 Reduced mobility in hyperconcentrated mud-grade calcite SGFs involves frictional forces,
507 which require particles to be close enough to rub against each other and thereby take forward
508 energy out of the flow. However, the 50% or more of fine CaCO_3 required for frictional forces
509 to become effective are less likely to occur in nature than the lower concentrations at which

510 turbulent forces dominate mud-grade calcite flows. It is therefore concluded that, purely from
511 the perspective of the lack of physical cohesion, mud-grade calcite SGFs should be highly
512 effective in moving suspended sediment away from shallow-water reefs, especially if a slope
513 is present, such as on the reef front and forereef.

514 This study provides a platform for further increases in the understanding of SGFs laden with
515 fine CaCO₃ by incorporating the influence of biological cohesion, particle density, and particle
516 shape on the sediment transport dynamics of SGFs above and around coral reefs and in other
517 carbonate environments. Given the high ecological, economic, and societal importance of
518 coral reefs and the threat imposed on reefs by anthropogenic climate change, a redressing of
519 the balance between studies of siliciclastic and calciclastic SGFs in favour of calciclastic SGFs
520 and their deposits is timely.

521

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530

531 **AUTHORS' CONTRIBUTIONS**

532 WH performed the laboratory experiments, did the data analysis and wrote the first draft of the paper.
533 JHB, SL and JH initiated the research, supervised the experiments and data analysis, and wrote the
534 final version of this paper.

535

536 **CONFLICT OF INTEREST STATEMENT**

537 The authors have no conflict of interest to declare.

538

539 DATA AVAILABILITY STATEMENT

540 The data that support the findings of this study are available from the corresponding author upon
541 reasonable request.

542

543 REFERENCES

544 Anthony, K.R.N., Kline, D.I., Diaz-Pulido, G., Dove, S. & Hoegh-Guldberg, O. (2008) Ocean acidification causes
545 bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of*
546 *the United States of America*, 105(45), 17442–17446.

547 Austin, J., Schlager, W. & Palmer, A (1986) Leg 101: Proceedings Initial Reports (Pt. A). Ocean Drilling Program,
548 College Station, Texas.

549 Azpiroz-Zabala, M., Cartingy, M.J.B., Talling, P.J., Parsons, D.R., Sumner, E.J., Clare, M.A., Simmons, S.M., Cooper,
550 C. & Pope, E.L. (2017) Newly recognized turbidity current structure can explain prolonged flushing of
551 submarine canyons. *Science Advances*, 3, e1700200.

552 Baas, J.H. & Best, J.L. (2002) Turbulence modulation in clay-rich sediment-laden flows and some implications for
553 sediment deposition. *Journal of Sedimentary Research*, 72, 336–340.

554 Baas, J.H., Best, J.L. & Peakall, J. (2011) Depositional processes, bedform development and hybrid bed formation
555 in rapidly decelerated cohesive (mud–sand) sediment flows. *Sedimentology*, 58, 1953–1987.

556 Baas, J.H., Best, J.L., Peakall, J. & Wang, M. (2009) A phase diagram for turbulent, transitional, and laminar clay
557 suspension flows. *Journal of Sedimentary Research*, 79, 162–183.

558 Baker, M.L., & Baas, J.H. (2023) Does sand promote or hinder the mobility of cohesive sediment gravity flows?
559 *Sedimentology*, 70, 1110–1130.

560 Baker, M.L., Baas, J.H. & Malarkey, J. (2017) The effect of clay type on the properties of cohesive sediment gravity
561 flows and their deposits. *Journal of Sedimentary Research*, 87, 1176–1195.

562 Barott, K.L., Rodriguez-Mueller, B., Youle, M., Marhaver, K.L., Vermeij, M.J.A., Smith, J.E. & Rohwer, F.L. (2011)
563 Microbial to reef scale interactions between the reef-building coral *Montastraea annularis* and benthic
564 algae. *Proceedings of the Royal Society B: Biological Sciences*, 279, 1655–1664.

565 Berkelmans, R. & van Oppen, M.J.H. (2006) The role of zooxanthellae in the thermal tolerance of corals: a ‘nugget
566 of hope’ for coral reefs in an era of climate change. *Proceedings of the Royal Society B*, 273, 2305–2312.

- 567 Betzler, C., Eberli, G.P. & Alvarez Zarikian, C.A. (2017). Maldives monsoon and sea level. *Proceedings of the*
568 *International Ocean Discovery Program, 359*, College Station, Texas.
- 569 Bian, C., Chen, J., Jiang, C., Wu, Z. & Yao, Z. (2023) Threshold of motion of coral sediment under currents in flume
570 experiments. *Sedimentology, 70*, 1723–1740.
- 571 Brodie, J. & Pearson, R.G.(2016) Ecosystem health of the Great Barrier Reef: Time for effective management
572 action based on evidence. *Estuarine, Coastal and Shelf Science, 183*, 438–451.
- 573 Brunner, C.A. (2021) Climate change doubles sedimentation-induced coral recruit mortality. *Science of the Total*
574 *Environment, 768*, 143897.
- 575 Chazottes, V., Reijmer, J.J.G. & Cordier, E. (2008) Sediment characteristics in reef areas influenced by
576 eutrophication-related alterations of benthic communities and bioerosion processes. *Marine Geology, 250*,
577 114–127.
- 578 Cinner, J. (2014) Coral reef livelihoods. *Current Opinion in Environmental Sustainability, 7*, 65–71.
- 579 Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S. & Turner, R.K.
580 (2014) Changes in the global value of ecosystem services. *Global Environmental Change, 26*, 152–158.
- 581 Craig, M.J., Baas, J.H., Amos, K.J., Strachan, L.J., Manning, A.J., Paterson, D.M., Hope, J.A., Nodder, S.D. & Baker,
582 M.L. (2020) Biomediation of submarine sediment gravity flow dynamics. *Geology, 48*, 72–76.
- 583 Crook, E.D., Cohen, A.L., Rebolledo-Vieyra, M., Hernandez, L & Paytan, A. (2013) Reduced calcification and lack
584 of acclimatization by coral colonies growing in areas of persistent natural acidification. *PNAS, 110*, 11044–
585 11049.
- 586 de Kruijf, M., Slotman, A., de Boer, R.A. & Reijmer, J.J.G. (2021) On the settling of marine carbonate grains:
587 Review and challenges. *Earth-Science Reviews, 217*, 103532.
- 588 Dyer, K.R. & Manning, A.J. (1999) Observation of the size, settling velocity and effective density of flocs, and
589 their fractal dimensions. *Journal of Sea Research, 41*, 87–95.
- 590 Eberli, G.P. (1987) Carbonate turbidite sequences deposited in rift-basins of the Jurassic Tethys Ocean (eastern
591 Alps, Switzerland). *Sedimentology, 34*, 363–388.
- 592 Eberli, G.P., Swart, P.K. & Malone, M.J. (1997) *Proceedings Ocean Drilling Program, Initial Reports, Leg 166*,
593 College Station, Texas, p. 850.
- 594 Eggenhuisen, J.T., McCaffrey, W.D., Haughton, P.D.W. & Butler, R.W.H. (2011) Shallow erosion beneath turbidity
595 currents and its impact on the architectural development of turbidite sheet systems. *Sedimentology, 58*,
596 936–959.
- 597 Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W. & Todd, P.A. (2012) Environmental impacts of dredging and other
598 sediment disturbances on corals: A review. *Marine Pollution Bulletin, 64*, 1737–1765.

- 599 Eriksson, R., Merta, J. & Rosenholm, J.B. (2007) The calcite/water interface: I. Surface charge in indifferent
600 electrolyte media and the influence of low-molecular-weight polyelectrolyte. *Journal of Colloid and*
601 *Interface Science*, 313, 184–193.
- 602 Evans, R.D., Wilson, S.K., Fisher, R., Ryan, N.M., Babcock, R., Blakeway, D., Bond, T., Dorji, P., Dufois, F., Fearn,
603 P., Lowe, R.J., Stoddart, J. & Thomson, D.P. (2020) Early recovery dynamics of turbid coral reefs after
604 recurring bleaching events. *Journal of Environmental Management*, 268, 110666.
- 605 Folk, R.L. & Ward W.C. (1957) Brazos river bar: A study in the significance of grain size parameters. *Journal of*
606 *Sedimentary Petrology*, 27, 3–26.
- 607 Gattuso, J.P., Allemand, D. & Frankignoulle, M. (1999) Photosynthesis and calcification at cellular, organismal
608 and community levels in coral reefs: A review on interactions and control by carbonate chemistry. *American*
609 *Zoologist*, 39, 160–183.
- 610 Haak, A.B. & Schlager, W. (1989) Compositional variations in calciturbidites due to sea-level fluctuations, late
611 Quaternary, Bahamas. *Geologische Rundschau*, 78, 477–486.
- 612 Hodson, J.M. & Alexander, J. (2010) The effects of grain density variation on turbidity currents and some
613 implications for the deposition of carbonate turbidites. *Journal of Sedimentary Research*, 80, 515–528.
- 614 Hubbard, D.K. (1986) Sedimentation as a control of reef development: St. Croix, U.S.V.I. *Coral Reefs*, 5, 117–125.
- 615 Hubbard, D.K., Miller, A.I. & Scaturro, D. (1990) Production and cycling of calcium carbonate in a shelf-edge reef
616 system (St. Croix, US Virgin Islands); Applications to the nature of reef systems in the fossil record. *Journal*
617 *of Sedimentary Petrology*, 60, 335–360.
- 618 Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen,
619 M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.-P.A., Hoey,
620 A.S., Hoogenboom, M., Lowe, R.J., McCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G. &
621 Wilson, S.K. (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*,
622 359, 80–83.
- 623 Jones, R., Giofre, N., Luter, H.M., Neoh, T.L., Fisher, R. & Duckworth, A. (2020) Responses of corals to chronic
624 turbidity. *Scientific Reports*, 10, 4762.
- 625 Kneller, B. & Buckee, C. (2000) The structure and fluid mechanics of turbidity currents: a review of some recent
626 studies and their geological implications. *Sedimentology*, 47, 62–94.
- 627 Langdon, C. & Atkinson, M.J. (2005) Effect of elevated pCO₂ on photosynthesis and calcification of corals and
628 interactions with seasonal change in temperature/irradiance and nutrient enrichment. *Journal of*
629 *Geophysical Research: Oceans*, 110, C09S07.
- 630 Lesser, M.P., Slaterry, M. & Leichter, J.J. (2009) Ecology of mesophotic coral reefs. *Journal of Experimental*
631 *Marine Biology and Ecology*, 375, 1–8.

- 632 Lirman, D. (2001) Competition between macroalgae and corals: Effects of herbivore exclusion and increased
633 algal biomass on coral survivorship and growth. *Coral Reefs*, 19, 392–399.
- 634 Liu, G., Wang, D., Chen, W., Wang, W., Betzler, C. & Han, X. (2023) Submarine landslides on a carbonate platform
635 slope changing transport pathways of deepwater gravity flows: Insights from the Xisha Islands, South China
636 Sea. *Geomorphology*, 437, 108813.
- 637 Lokier, S.W. (2023) Marine carbonate sedimentation in volcanic settings. In: Di Capua, A., De Rosa, R., Kereszturi,
638 G., Le Pera, E., Rosi, M. & Watt, S.F.L. (Eds) *Volcanic processes in the sedimentary record: When volcanoes
639 meet the environment*, Geological Society, London, Special Publication, 520, 547–594.
- 640 Lokier, S.W., Wilson, M.E.J. & Burton, L.M. (2009) Marine biota response to clastic sediment influx: A quantitative
641 approach. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 281, 25–42.
- 642 Lopez-Gamundi, C., Barnes, B.B., Bakker, A.C., Harris, P., Eberli, G.P. & Purkis, S.J. (2024) Spatial, seasonal, and
643 climatic drivers of suspended sediment atop Great Bahama Bank. *Sedimentology*, 71, 769–792.
- 644 MacDonald, I.A. & Perry, C.T. (2003) Biological degradation of coral framework in a turbid lagoon environment,
645 Discovery Bay, north Jamaica. *Coral Reefs*, 22, 523–535.
- 646 Mallela, J. & Perry, C.T. (2006) Calcium carbonate budgets for two coral reefs affected by different terrestrial
647 runoff regimes, Rio Bueno, Jamaica. *Coral Reefs*, 26, 129–145.
- 648 Marr, J.G., Harff, P.A., Shanmugam, G. & Parker, G. (2001) Experiments on subaqueous sandy gravity flows: The
649 role of clay and water content in flow dynamics and depositional structures. *Geological Society of America
650 Bulletin*, 113, 1377–1386.
- 651 Mass, T., Einbinder, S., Brokovich, E., Shashar, N., Vago, R., Erez, J. & Dubinsky, Z. (2007) Photoacclimation of
652 *Stylophora pistillata* to light extremes: metabolism and calcification. *Marine Ecology Progress Series*, 334,
653 93–102.
- 654 Mehta, A.J., Hayter, E.J., Parker, R., Krone, R.B. & Teeter, A.M. (1989) Cohesive sediment transport. 1: Process
655 description. *Journal of Hydraulic Engineering*, 115, 1076–1093.
- 656 Middleton, G.V. & Hampton, M.A. (1973) Part 1. Sediment gravity flows: Mechanics of flow and deposition. In:
657 Middleton, G.V. & Bouma, A.A. (Eds) *Turbidites and deep-water sedimentation*, SEPM Pacific Section Short
658 Course Notes, Anaheim, California, p. 38.
- 659 Mohrig, D. & Marr, J.G. (2003) Constraining the efficiency of turbidity current generation from submarine debris
660 flows and slides using laboratory experiments. *Marine and Petroleum Geology*, 20, 883–899.
- 661 Mulder, T. & Alexander, J. (2001) The physical character of subaqueous sedimentary density flow and their
662 deposits. *Sedimentology*, 48, 269–299.

- 663 Parker, G. (1987) Experiments on turbidity currents over an erodible bed. *Journal of Hydraulic Research*, 25, 123–
664 147.
- 665 Pashley, R.M. & Karaman, M.E. (2004) *Applied Colloid and Surface Chemistry*. London: John Wiley & Sons, p. 188.
- 666 Payros, A. & Pujalte, V. (2008) Calciclastic submarine fans: An integrated overview. *Earth-Science Reviews*, 86,
667 203–246.
- 668 Perry, C.T., Salter, M.A., Harborne, A.R., Crowley, S.F., Jelks, H.L. & Wilson, R.W. (2011) Fish as major carbonate
669 mud producers and missing components of the carbonate factory. *Proceedings of the National Academy of*
670 *Sciences*, 108, 3865–3869.
- 671 Perry, C.T., Kench, P.S., O’Leary, M.J., Morgan, K.M. & Januchowski-Hartley, F. (2015) Linking reef ecology to
672 island building: Parrotfish identified as major producers of island-building sediment in the Maldives.
673 *Geology*, 43, 503–506.
- 674 Postma, G. (2011) Sediment gravity flow. In: Singh, V.P., Singh, P. & Haritashya, U.K. (Eds), *Encyclopedia of snow,*
675 *ice and glaciers*, Geology Faculty Publications, Paper 7, University of Dayton, Ohio, 1005–1010.
- 676 Reijmer, J.J.G., Palmieri, P. & Groen, R. (2012) Compositional variations in calciturbidites and calcidebrites in
677 response to sea-level fluctuations (Exuma Sound, Bahamas). *Facies*, 58, 493–507.
- 678 Reijmer, J.J.G., Schlager, W., Bosscher, H., Beets, C.J. & McNeill, D.F. (1992) Pliocene/Pleistocene platform facies
679 transition recorded in calciturbidites (Exuma Sound, Bahamas). *Sedimentary Geology*, 78, 171–179.
- 680 Rogers, C.S. & Ramos-Scharrón, C.E. (2022) Assessing effects of sediment delivery to coral reefs: A Caribbean
681 watershed perspective. *Frontiers in Marine Science*, 8, 773968.
- 682 Rogers, C.S. (1990) Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress*
683 *Series*, 62, 185–202.
- 684 Russ, G.R., Questel, S.L.A., Rizzari, J.R. & Alcalá, A.C. (2015) The parrotfish–coral relationship: Refuting the
685 ubiquity of a prevailing paradigm. *Marine Biology*, 162, 2029–2045.
- 686 Salter, M.A., Perry, C.T. & Wilson, R.W. (2012) Production of mud-grade carbonates by marine fish: Crystalline
687 products and their sedimentary significance. *Sedimentology*, 59, 2172–2198.
- 688 Schieber, J., Southard, J.B., Kissling, P., Rossman, B. & Ginsburg, R. (2013) Experimental deposition of carbonate
689 mud from moving suspensions: Importance of flocculation and implications for modern and ancient
690 carbonate mud deposition. *Journal of Sedimentary Research*, 83, 1025–1031.
- 691 Scoffin, T. (1993) The geological effects of hurricanes on coral reefs and the interpretation of storm deposits.
692 *Coral Reefs*, 12, 203–221.
- 693 Sheppard, C., Davy, S., Pilling, G. & Graham, N. (2017) *The Biology of Coral Reefs*. Oxford: Oxford University Press,
694 p. 384.

- 695 Slooman, A., de Kruijf, M., Glatz, G., Eggenhuisen, J.T., Zühlke, R. & Reijmer, J.J.G. (2023) Shape-dependent
696 settling velocity of skeletal carbonate grains: Implications for calciturbidites. *Sedimentology*, 70, 1683–
697 1722.
- 698 Sobocinska, A. & Baas, J.H. (2022) Effect of biological polymers on mobility and run-out distance of cohesive and
699 non-cohesive sediment gravity flows. *Marine Geology*, 452, 106904.
- 700 Spalding, M.D. (2001) *World Atlas of Coral Reefs*. California: University of California Press, p. 424.
- 701 Spalding, M.D, Ruffo, S., Lacambra, C., Meliane, I., Hale, L., Shepard, C.C. & Beck, M.W. (2014) The role of
702 ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean & Coastal*
703 *Management*, 90, 50–57.
- 704 Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley,
705 P.M. (2013) *Climate change 2013: The physical science basis. Contribution of working group I to the fifth*
706 *assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press,
707 Cambridge, United Kingdom and New York, NY, USA, p. 1535.
- 708 Sumner, E.J., Talling, P.J. & Amy, L.A. (2009) Deposits of flows transitional between turbidity current and debris
709 flow. *Geology*, 37, 991–994.
- 710 Swart, P.K., Eberli, G.P., Malone, M.J. & Sarg, J.F. (2000) *Proceedings Ocean Drilling Program, Leg 166, Scientific*
711 *Results*, College Station, Texas, p. 213.
- 712 Talling, P.J. (2014) On the triggers, resulting flow types and frequencies of subaqueous sediment density flows
713 in different settings. *Marine Geology*, 352, 155–182.
- 714 Talling, P.J., Allin, J., Armitage, D.A., Arnott, R.W.C., Cartigny, M.J.B., Clare, M.A., Felletti, F., Covault, J.A.,
715 Girardclos, S., Hansen, E., Hill, P.R., Hiscott, R.N., Hogg, A.J., Clarke, J.H., Jobe, Z.R., Malgesini, G., Mozzato,
716 A., Naruse, H., Parkinson, S., Peel, F.J., Piper, D.J.W., Pope, E., Postma, G., Rowley, P., Sguazzini, A.,
717 Stevenson, C.J., Sumner, E.J., Sylvester, Z., Watts, C. & Xu, J. (2015) Key future directions for research on
718 turbidity currents and their deposits. *Journal of Sedimentary Research*, 85, 153–169.
- 719 Talling, P.J., Masson, D.G., Sumner, E.J. & Malgesini, G., 2012, Subaqueous sediment density flows: Depositional
720 processes and deposit types. *Sedimentology*, 59, 1937-2003.
- 721 Tanner, J.E. (1995) Competition between scleractinian corals and macroalgae: An experimental investigation of
722 coral growth, survival and reproduction. *Journal of Experimental Marine Biology and Ecology*, 190, 151–
723 168.
- 724 Trower, E.J., Lamb, M.P. & Fischer, W.W. (2019) The origin of carbonate mud. *Geophysical Research Letters*, 46,
725 2696–2703.
- 726 Tuttle, L.J. & Donahue, M.J. (2022) Effects of sediment exposure on corals: A systematic review of experimental
727 studies. *Environmental Evidence*, 11:4, 33 p.

- 728 Venn, A.A., Tambutté, E., Caminiti-Segonds, N., Techer, N., Allemand, D. & Tambutté, S. (2019) Effects of light
729 and darkness on pH regulation in three coral species exposed to seawater acidification. *Scientific Reports*,
730 9, 2201.
- 731 Wilson, M.E.J. (2012) Equatorial carbonates: An earth systems approach. *Sedimentology*, 59, 1–31.

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732 TABLE AND FIGURE CAPTIONS

733 TABLE 1 Generic sediment gravity flow type classification scheme of Baker & Baas (2023)
734 applied to the CaCO₃-laden flows used in this study (modified after Baker & Baas, 2023)

735 TABLE 2 Summary of experimental data of this study (mud-grade calcite) and Baker et al.
736 (2017) (kaolinite, bentonite, silica flour)

737 FIGURE 1 Experimental setup used for the lock-exchange tank experiments. The tank is 0.2
738 m wide and the slope of the tank was set to 0° in all experiments (after Baker et al. 2017)

739 FIGURE 2 Frequency distribution curve of the particle size of the mud-grade calcite used in
740 the experiments. Particle size is given in ϕ (phi)-values

741 FIGURE 3 Video stills of the heads of selected CaCO₃ flows. (A) 15% low-density turbidity
742 current, (B) 25% low-density turbidity current, (C) 53% high-density turbidity current, (D) 55%
743 high-density turbidity current, (E) 58% mud flow, and (F) 59% slide. Dashed lines in (C) and (D)
744 show density interfaces in high-density turbidity currents. Arrow in (E) points to lip region of
745 mud flow. Scale bar is 100 mm long

746 FIGURE 4 Head velocity against downflow distance from the lock gate for: (A) 1% to 30%
747 mud-grade calcite flows; and (B) 35% to 59% mud-grade calcite flows. Low-density turbidity
748 currents, high-density turbidity currents, mud flows, and slides are given in blue, green, red,
749 and black, respectively

750 FIGURE 5 Deposit thickness trends of mud-grade calcite flows that had a measurable run-
751 out distance. High-density turbidity currents, mud flow, and slide are given in green, red, and
752 black, respectively

753 FIGURE 6 Maximum head velocity of CaCO₃, kaolinite, bentonite, and silica flour flows
754 against initial suspended sediment concentration

755 FIGURE 7 Run-out distance of CaCO₃, kaolinite, bentonite, and silica flour flows against
756 initial suspended sediment concentration. Run-out distances of 4.69 m denote minimum
757 values; these flows reflected off the end of the tank

758 FIGURE 8 Deposit thickness trends of mud-grade calcite and silica-flour flows against
759 downflow distance from the lock gate, comparing selected high-density turbidity currents
760 (HDTCs), mud flows, and slides from this study and Baker et al. (2017)

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1 **Coming to light: How effective are sediment gravity flows in**
2 **removing fine suspended carbonate from reefs?**

3
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12
13
14 **Abstract**

15 Coral reefs are hard calcified structures, mainly found in warm tropical water. These
16 ecosystems serve an important role as, for example, a source of food, shelter and nursery for
17 different organisms, and coastal protection. Reef-building organisms have evolved to inhabit
18 a narrow ecological niche and thus are particularly susceptible to rapid changes in their
19 environment, e.g., under predicted climate-change scenarios. Anthropogenic climate change
20 is widely accepted as the leading cause of rising ocean temperatures, seawater acidity and
21 sedimentation rate, which all affect a coral's productivity, health and, to some extent, skeletal
22 strength. High-energy weather events, such as storms and hurricanes, can erode reefs,
23 thereby increasing the amount of suspended sediment and consequently the turbidity of the
24 water. The removal of suspended sediment from the reef is vital for the health of reef
25 producers, and a natural process that removes suspended sediment from reefs are sediment
26 gravity flows. A key factor that controls the ability of sediment gravity flows to transport

27 sediment is cohesion, as cohesion determines the run-out distance of a flow through changes
28 in its rheological properties. This study examines the cohesive nature of sediment gravity
29 flows laden with fine-grained CaCO_3 . These ~~lime-mud laden~~ gravity flows laden with mud-
30 grade calcite are compared with flows carrying non-cohesive, silt-sized, silica flour, weakly
31 cohesive kaolinite clay, and strongly cohesive bentonite clay, by means of laboratory
32 experiments. The results of these experiments show that the mud-grade calcite ~~lime-mud~~
33 flows behave more akin to the silica-flour flows by reaching maximum mobility at
34 considerably higher volumetric suspended sediment concentrations (47% for silica flour and
35 53% for CaCO_3) than the kaolinite and bentonite flows (22% for kaolinite and 16% bentonite).
36 Fine CaCO_3 gravity flows can therefore be regarded as physically non-cohesive, and their high
37 mobility may constitute an effective mechanism for removing suspended sediment from coral
38 reefs, especially at locations where a slope gradient is present, such as at the reef front and
39 forereef. However, biological cohesion, caused by 'sticky' extracellular polymer substances
40 produced by micro-organisms, can render mud-grade calcite ~~lime-mud~~ cohesive and sediment
41 gravity flows less mobile. The present study should therefore be seen as a first step towards
42 a more comprehensive analysis of the efficiency of removal of suspended sediment from coral
43 reefs.

44

45 **KEYWORDS**

46 Mud-grade calcite ~~Lime-mud~~, Sediment gravity flows, Cohesion, Laboratory experiments

47

48 **1 | INTRODUCTION**

49 Sediment gravity flows (SGFs) are amongst the most important sediment transport processes
50 on Earth, providing large quantities of sediment, carbon, nutrients and pollutants, such as
51 microplastics, to lakes, seas, and oceans (e.g., Kneller & Buckee, 2000; Postma, 2011; Talling,
52 2014). In the ocean, SGFs can cause considerable damage to underwater communication
53 cables and other deep-water engineering infrastructure (Talling et al., 2015). Although most
54 research on SGFs has focussed on siliciclastic sediment transport and environments, their
55 deposits are common also in modern and ancient carbonate environments (e.g., Austin et al.,

56 1986; Eberli, 1987; Eberli et al., 1997; Swart et al., 2000; Payros & Pujalte, 2008; Betzler et al.,
57 2017; Liu et al., 2023). Yet, process-based research of carbonate-laden gravity flows, and
58 comparisons with siliciclastic gravity flows, is relatively rare (e.g., Hodson & Alexander, 2010).
59 A recent paper by Slooman et al. (2023) summarised the present knowledge of the physics
60 of carbonate-sand laden SGFs and analysed the effect of carbonate particle shape and density
61 on their settling velocity in SGFs and their distribution in SGF deposits. Slooman et al. (2023)
62 concluded that “in addition to grain size and particle density, the irregular shape of skeletal
63 sediments exerts a significant control on the distribution of sand grains in calciturbidites”, but
64 their work did not include calciclastic, fine-grained sediment. Below, the term ‘mud-grade
65 calcite’ ~~lime mud~~’ is used to describe this sediment in a purely granulometric sense, i.e., a
66 mixture of silt and clay-sized CaCO₃ particles, without reference to a specific physical,
67 biological or chemical origin (e.g., Hubbard et al., 1990).

68 Fine-grained sediment, including mud-grade calcite~~lime mud~~, can be cohesive, ‘sticky’, which
69 has wide-ranging implications for the dynamic behaviour, i.e., ‘mobility’, of SGFs (e.g., Marr
70 et al., 2001, Mohrig & Marr, 2003; Sumner et al., 2009; Baas et al., 2009, 2011; Baker et al.,
71 2017), as cohesion works against the gravity-induced principle that flow velocity increases as
72 suspended sediment concentration increases. Particle attraction by cohesion in SGFs can have
73 physical and biological origins (Craig et al., 2020) and these cohesive forces work against
74 turbulent forces to decrease the mobility of SGFs (Baas et al., 2009, 2011). In siliciclastic-clay
75 laden flows, the decrease in mobility may start at a volumetric clay concentration of c. 10%
76 (Baker et al., 2017), although this threshold varies with flow velocity, i.e., turbulence intensity;
77 stronger turbulence leads to more breakage of electrostatic bonds between fine particles.
78 Mud-grade calcite ~~Lime mud~~ consists of fine-grained calcium carbonate that can be entrained,
79 in conjunction with coarser sediment, into the water column in large quantities on carbonate
80 platforms (including reefs) during storms and subaqueous slope failures. This resuspended
81 sediment may then be shed offshore by SGFs (Haak & Schlager, 1989; Reijmer et al., 1992,
82 2012; and further references in Slooman et al., 2023). The origin of mud-grade calcite ~~lime~~
83 ~~mud~~ can be biological, chemical, and detrital (Hubbard, 1990; MacDonald & Perry, 2003; Perry
84 et al., 2015; Russ et al., 2015; Trower et al., 2019). The production of mud-grade calcite ~~lime~~
85 ~~mud~~ is a common process on carbonate platforms. However, it is particularly important for
86 unhealthy, brittle reefs subjected to environmental stress, such as coral bleaching, because

87 their weakened skeleton renders these reefs more susceptible to: (a) physical erosion and
88 subsequent production of mud by abrasion of eroded sand and rubble (Trower et al., 2019),
89 and (b) biological erosion and production of mud by scrapers and excavators, e.g., parrot fish
90 and urchins ([Salter et al., 2012](#); Perry et al., 2015; Russ et al., 2015), cyanobacterial infestation,
91 post-mortem disintegration of calcareous algae, and micro and macroborers, e.g., sponges
92 (MacDonald & Perry, 2003; Perry et al., 2015).

93 Generally, the presence of large volumes of suspended mud is detrimental to carbonate
94 producers and, thus, to sediment production and reef growth (e.g., Rogers & Ramos-
95 Scharrón, 2022; Tuttle & Donahue, 2022). Carbonate production is highest in sessile benthic
96 organisms precipitating skeletal material in association with photosynthesis. This process is
97 optimum in shallow clear waters within the uppermost few metres of the photic zone. The
98 presence of mud in the water column reduces the depth of the photic zone and, thus, reduces
99 the incident light at the sea floor — a process akin to an increase in water depth. Turbidity
100 can have a major impact on gross carbonate production, taphonomy and sediment
101 production of reefs (e.g., Mallela & Perry, 2006). Where mud settles onto the reef surface,
102 carbonate producers may be stressed, or even killed, through ingestion or smothering (Lokier
103 et al., 2009; Lokier, 2023).

104 The aim of this paper is to determine, at first order, how effective SGFs are, in addition to
105 wind, waves, and tides (e.g., Lopez-Gamundi et al., 2024), in shedding fine suspended CaCO_3
106 sediment off reefs, considering that removal of suspended sediment from the water column
107 above reefs is needed to clear turbid water and aid the maintenance of reef health (e.g., Jones
108 et al., 2020). Experimental research was used to compare the head velocity, run-out distance,
109 and deposit shape of ~~lime-mud-laden~~ flows laden with mud-grade calcite (crushed limestone)
110 with non-cohesive siliciclastic silt flows and cohesive siliciclastic clay flows. This comparison
111 aims to derive a descriptive measure of the degree of cohesion of ~~lime-mud-laden~~ SGFs laden
112 with mud-grade calcite. The hypothesis is that, if fine CaCO_3 flows are non-cohesive, the low
113 settling velocity of the mud-grade calcite ~~lime-mud~~ renders these flows highly mobile and well
114 able to remove suspended sediment from reefs after storms. The specific objectives of this
115 research are therefore:

- 116 1. to determine if SGFs laden with mud-grade calcite (crushed limestone) ~~lime-mud~~ are
117 physically cohesive or non-cohesive;

118 2. to quantify changes in mobility of ~~lime-mud~~ mud-grade calcite SGFs and deposit shape as
119 a function of suspended CaCO₃ concentration;

120 3. to discuss differences between healthy and unhealthy, brittle reefs in the efficiency of
121 CaCO₃-laden flows to clean turbid water, especially after storms;

122 4. to consider the potential effect of biological cohesion and particle shape and density on
123 the mobility of SGFs laden with mud-grade calcite in view of future research.

124 ~~4.5. to discuss differences between healthy and unhealthy, brittle reefs in the efficiency of~~
125 ~~CaCO₃-laden flows to clean turbid water, especially after storms.~~

126

127 **2 | BACKGROUND AND RATIONALE**

128 **2.1 | Coral reefs**

129 Coral reefs are amongst the largest and most complex ecosystems on Earth, primarily found
130 in warm waters in the tropics (Spalding, 2001). Most reef-forming scleractinian corals host
131 symbiotic dinoflagellate zooxanthellae that use light to provide nutrients to the coral
132 (Berkelmans & van Oppen, 2006). Millions of species worldwide call reefs their home
133 (Sheppard et al., 2017) and an estimated 6 million people around the globe are dependent on
134 coral reefs (Cinner, 2014). Reefs supply job opportunities to local communities and they
135 provide a food source and recreational opportunities, such as diving and eco-tourism
136 (Costanza et al., 2014). Reefs also support coastal communities by providing protection
137 against coastal hazards. As such, coral reefs act like sandbars and barrier islands by dispersing
138 wave energy from storms and hurricanes (Spalding et al., 2014).

139 Because of the delicate relationship with zooxanthellae, coral reefs are sensitive to outside
140 stressors, such as heat, acidification, and sedimentation. Coral species, in particular, are
141 susceptible to change. If the external stressors become too strong, the zooxanthellae are
142 expelled from the coral, leaving them colourless (bleached). The world's oceans have been
143 warming since the rise of the industrial revolution, in parallel with the increase of atmospheric
144 carbon. Carbon dioxide gas traps heat close to the Earth surface, with the oceans serving as a
145 heat sink (Stocker et al., 2013). The increased seawater temperature negatively affects the
146 health of coral reefs, which can only thrive within a narrow water temperature range (Wilson,
147 2012). A direct consequence of rising oceanic CO₂ levels is ocean acidification. This happens

148 when seawater and CO_2 mix to make CO_3^{2-} (carbonate), HCO_3^- (bicarbonate) and
149 H^+ (hydrogen), which lowers the pH. As a result of ocean acidification, corals cannot produce
150 calcium carbonate as easily (e.g., Langdon & Atkinson, 2005). Reefs that have undergone
151 bleaching because of rising seawater temperature and possibly also ocean acidification
152 (Anthony et al., 2008) are more delicate than healthy reefs. In the period between 1980 and
153 2016, the years 1998, 2005, 2010, and 2016 had particularly high numbers of bleaching events
154 around the world (Hughes et al., 2018). Without a strong calcified outer layer, a coral is more
155 susceptible to physical and biological erosion (MacDonald & Perry, 2003; Perry et al., 2015;
156 Russ et al., 2015; Trower et al., 2019). Reefs in the tropics suffer regular high energy events,
157 as hurricane-generated waves and storm surges are common at these latitudes. During these
158 events, corals as far down as 20 m can be affected, with certain growth forms, such as
159 branching corals, being particularly susceptible (Scoffin, 1993). It is therefore hypothesised
160 that an unhealthy, brittle reef produces more suspended sediment, including mud-grade
161 calcite lime mud via abrasion of sand and gravel (Trower et al., 2019), during a storm or
162 hurricane than a stronger, more calcified, healthy reef. The problem is compounded by the
163 fact that reefs that have been affected by natural or anthropogenic disturbances exhibit
164 slower coral recovery rates under higher turbidity conditions (Evans et al., 2020). Moreover,
165 anthropogenic eutrophication causes a change in the balance of coral versus coralline algae
166 within the reefs (e.g., Chazottes et al., 2008), which further exacerbates the production of
167 large amounts of mud-grade carbonate sediment by, in particular, biological erosion.

168 The amount of sediment input to reefs from anthropogenic sources, such as remobilisation
169 by fishing and dredging, has increased substantially (Brodie & Pearson, 2016). High levels of
170 suspended sediment above and around coral reefs make the water more turbid, reducing the
171 light penetration to the corals and hindering photosynthesis and zooxanthellae productivity
172 (Rogers, 1990). Sediment settling on coral tissue causes further shading and smothering.
173 Healthy corals can actively remove small amounts of sediment from their tissues via ciliary
174 activity, hydrostatic expansion, tentacle movements, and mucus production (Brunner, 2021),
175 but unhealthy corals are less able to do so. Shading and smothering contribute to a further
176 decrease in the productivity of the photosynthesising zooxanthellae; this is another major
177 cause of coral bleaching (Erftemeijer et al., 2012). Where smothering is significant, corals, and
178 other sessile benthic carbonate producers, will be killed through anoxia or tissue narcosis

179 (references in Lokier, 2023). Even small amounts of smothering may kill carbonate producers,
180 as an inability to feed results in starvation. Calcification rates are three times higher in light
181 conditions than in dark conditions, and recent studies have suggested that calcification is
182 dark-repressed rather than light-enhanced (e.g., Venn et al., 2019). Thus, a coral reef in
183 seawater with high amounts of suspended sediment calcifies less (Gattuso, 1999). This lower
184 calcification rate results in the construction of a weaker skeleton and, thus, higher
185 vulnerability of the reef to biological erosion (MacDonald & Perry, 2003; Perry et al., 2015;
186 Russ et al., 2015) and mechanical breakdown during storms (Crook et al., 2013). In turn, more
187 suspended sediment needs to be transported away from the reef after storm events to ensure
188 coral productivity and health.

189

190 **2.2 | Sediment gravity flows**

191 Sediment gravity flows (SGFs) are known to shed suspended sediment off reefs into deeper
192 water (Haak & Schlager, 1989; Reijmer et al., 1992, 2012; and further references in Slotman
193 et al., 2023), but SGFs vary significantly in their efficiency of transporting sediment, i.e., in
194 flow mobility. The controls on the mobility of SGFs can be summarised by four main factors:
195 (1) flow type, which can be laminar, transitional, or turbulent; (2) flow behaviour, which can
196 be cohesive or non-cohesive; (3) excess density of the flow, relative to the ambient water;
197 and (4) substrate slope gradient (Talling et al., 2012). The present paper focusses on cohesion
198 and excess density, here expressed as volumetric sediment concentration. Depending on flow
199 type and rheology, SGFs can behave as a fluid or plastic. Examples of fluidal flows used in this
200 paper are low-density and high-density turbidity currents (Baker et al., 2017). Mud flows and
201 slides, also used in this paper, are examples of plastic flow (Baker et al., 2017).

202 Following the definitions of Baker et al. (2017), low-density turbidity currents are fully
203 turbulent, i.e., well-mixed flows without an internal density interface (Table 1; Baker et al.,
204 2017). High-density turbidity currents (Baker et al., 2017) have two distinct layers: a low-
205 density, fully turbulent cloud of suspended sediment in the upper part separated by a density
206 interface from a high-density layer with reduced turbulence in the lower part of the flow
207 (Table 1). Mud flows are defined as high-concentration, laminar SGFs without significant
208 internal turbulence, in which a cohesive clay gel provides grain support by matrix strength

209 (Middleton & Hampton, 1973; Baker et al., 2017). Mud flows may have a dilute top, caused
210 by minor mixing with the ambient water. A slide is a coherent mass flow without significant
211 internal deformation, formed at the highest suspended sediment concentrations (Table 1;
212 Baker et al., 2017).

213 **2.3 | Cohesion**

214 SGFs can be subdivided in non-cohesive, dominantly fluidal, flow types and cohesive,
215 dominantly plastic, flow types. Cohesive SGFs are more complex than non-cohesive SGFs,
216 because of the ability of clay particles to form aggregates (floccules) and gels (e.g., Mehta et
217 al., 1989). The presence of floccules and gels increases the viscosity and yield strength and
218 modulates the turbulence maintaining the flow (Baas & Best, 2002). Floccule size generally
219 increases as bulk suspended-clay concentration increases (Dyer & Manning, 1999) until a
220 gelling point is reached, at which a volume-filling network of clay particle bonds in the liquid,
221 i.e., a gel, establishes.

222 Settling of clay particles is dependent on the concentration — and less so on the size — of
223 individual clay particles, if the settling is controlled by the aggregation and gelling processes
224 (Dyer & Manning, 1999). In low-concentration suspensions, in which flocs are small, the
225 settling velocity and concentration are independent of each other. However, in high-
226 concentration suspensions, particles are more likely to form large flocs, which usually have a
227 greater submerged weight, and therefore a higher settling velocity (Dyer & Manning, 1999).
228 Clay gelling inhibits the turbulence of the flow through increased viscosity (Baker et al., 2017).
229 Flows that behave as a gel tend to deposit 'en masse'. This bulk settling process involves a
230 positive feedback mechanism, 'cohesive freezing' (Mulder & Alexander , 2001). Cohesive
231 freezing typically follows a reduction in the head velocity of the flow, which decreases
232 turbulent forces, allowing the clay minerals to form a greater number of electrostatic bonds,
233 in turn increasing cohesive strength. This then further reduces the turbulence and results in
234 a rapid further reduction in the head velocity of the flow. This deceleration process repeats
235 itself until the flow swiftly comes to a halt. The equivalent process in non-cohesive, usually
236 silt-laden, SGFs is 'frictional freezing'. Frictional freezing takes place at considerably higher
237 sediment concentrations than cohesive freezing, because non-cohesive particles do not form
238 gels (Baker et al., 2017).

239 2.4 | Research approach

240 In order to estimate how effectively fine suspended CaCO_3 sediment can be transported by
241 SGFs, lock-exchange experiments were conducted with mud-grade calcite lime-mud-gravity
242 flows. The experiments comprised a full range of initial suspended sediment concentrations,
243 covering low-density and high-density turbidity currents, mud flows, and slides (sensu Baker
244 et al., 2017). The observation that flows carrying fine non-cohesive siliciclastic particles (silica
245 flour in Table 2) are highly mobile up to volumetric concentrations of 52% and equivalent
246 cohesive SGFs lose mobility at much lower concentrations, e.g., at 20% for bentonite clay
247 (Table 2; Baker et al., 2017), allows us to estimate the cohesive properties of the mud-grade
248 calcite lime-mud-flows through comparison of head velocity, run-out distance, and deposit
249 shape, following procedures used by Craig et al. (2020), Sobocinska & Baas (2022) and Baker
250 & Baas (2023) for siliciclastic sediment. In turn, this information is used to discuss how
251 effective mud-grade calcite lime-mud-SGFs can be in cleaning turbid water above reefs,
252 primarily based on the degree of cohesion, but also taking other controls on flow mobility,
253 such as biological cohesion, into consideration.

254

255 3 | METHODS AND MATERIALS

256 Fifteen lock-exchange experiments were conducted in the Hydrodynamics Laboratory of
257 Bangor University (NW Wales, U.K.) between October 2022 and February 2023. The lock-
258 exchange tank is 5 m long, 0.2 m wide, and 0.5 m deep (Figure 1). It is made up of two sections:
259 a 0.31-m long reservoir separated from the 4.69-m long main body by a lock gate. The slope
260 of the tank was set to 0° in all experiments to allow direct comparison with the siliciclastic
261 flows studied by Baker et al. (2017), to minimize the number of variables, and to achieve a
262 minimum requirement for mud removal, as slopes promote flow and favour turbulent driving
263 forces over mobility-reducing cohesive forces. For each experiment, the reservoir was filled
264 with a mixture of seawater and fine-grained calcium carbonate particles to a depth of 0.35 m
265 (Figure 1). The remainder of the tank was filled simultaneously with seawater to the same
266 level as in the reservoir. The seawater was sourced from the Menai Strait (NW Wales, U.K.)
267 and filtered to remove suspended particles before application. The salinity and temperature
268 of the seawater were 35 psu and c. 15°C , respectively. As a first-order approximation of

269 natural ~~mud-grade calcite~~~~lime-mud~~, the calcium carbonate used in the experiments consists
270 of crushed limestone (calcite) without significant intraparticle porosity, manufactured by
271 Omya® (C.A.S. number 1317-65-3) and supplied under the name “Calcium Carbonate Powder”
272 by Elixir Garden Supplies in the U.K. The size distribution of the ~~mud-grade calcite~~ ~~lime-mud~~
273 was measured using a Microtrac Sync laser particle sizer at the School of Ocean Sciences,
274 Bangor University. The ~~mud-grade calcite~~ ~~lime-mud~~ is a very poorly sorted sandy mud with a
275 median size of 0.009 mm (6.9 ϕ : fine silt) and a sorting coefficient of 2.466 (Folk & Ward, 1957).
276 Figure 2 shows two main modal sizes at 0.0025 mm (8.6 ϕ : clay) and 0.060 mm (4.1 ϕ : coarse
277 silt). The volumetric concentration of CaCO₃ in the flows ranged from 1% to 59%.

278 A consistent method was used to prepare each mixture of seawater and ~~mud-grade calcite~~
279 ~~lime-mud~~ to account for any settling and time-dependent rheological behaviour. Volumetric
280 suspended sediment concentrations were determined from the density, ρ , and required mass
281 of CaCO₃ and seawater, with $\rho_{\text{~~mud-grade calcite~~ ~~lime-mud~~}} = 2710 \text{ kg m}^{-3}$ and $\rho_{\text{seawater}} = 1027 \text{ kg m}^{-3}$.
282 The total volume of the mixture was 0.02446 m³. This was sufficient to fill the reservoir to a
283 depth of 0.4 m, thus allowing for some loss of the mixture during preparation. Dry CaCO₃ and
284 seawater were mixed for 10 minutes in a concrete mixer. Thereafter, the suspension was
285 decanted in a container and the walls of the mixer were scraped down to ensure that as little
286 as possible of the mixture was left in the mixer. The suspension was then mixed with a
287 handheld mixer for a further 3 minutes to make sure the mixture was free of lumps.
288 Subsequently, the mixture was transferred to the reservoir whilst the main body of the tank
289 filled with seawater, to avoid leakage because of pressure differences between both sides of
290 the lock gate. Immediately before lifting the gate and starting an experiment, the mixture in
291 the reservoir was homogenised for 60 s with the handheld mixer. A HD video camera,
292 attached to runners on top of the tank, tracked the front of the flow along the tank. The video
293 recordings were used to describe and classify the SGFs (cf., Baker et al., 2017) and determine
294 the mean velocity of the head of the flow at each 0.1 m distance along the flow path, as well
295 as the run-out distance of flows that did not reach the end of the tank. Deposit thicknesses
296 were measured with electronic callipers and rulers, but only for flows that did not reflect off
297 the end wall, as these reflections disturbed the deposits. Maximum head velocity of the flows
298 along the tank is used throughout this paper to allow a comparison with previous work on
299 siliciclastic silt and clay flows.

300

301 **4 | RESULTS**

302 The experimental data for the mud-grade calcite lime-mud experiments are summarised in
303 Table 2, which also shows the experimental results of Baker et al. (2017) for kaolinite clay,
304 bentonite clay, and silica flour that were conducted using the same method. Figure 3 depicts
305 the heads of selected mud-grade calcite lime-mud flows. Figure 4 shows changes in head
306 velocity with distance along the tank for all flows, and Figure 5 summarises changes in deposit
307 thickness with distance along the tank.

308 **4.1 | Visual observations**

309 The videos reveal that the 1% to 45% mud-grade calcite lime-mud flows were all fully
310 turbulent between base and top (Figure 3A, B) and had a semi-elliptically shaped head and
311 distinct Kelvin-Helmholtz instabilities at their upper boundary in vertical cross-section parallel
312 to the flow direction. These flows kept their forward momentum to the end of the tank,
313 suggesting that the turbulence in these flows was able to outcompete the particle settling
314 and kept most particles in suspension until the flows reflected off the end wall. These
315 properties match the low-density turbidity current type of Baker et al. (2017) (Table 1).

316 The flows laden with 50%, 53% and 55% mud-grade calcite lime-mud had two distinct parts
317 separated by a density interface (dashed white line in Figure 3C, D). The upper part of these
318 flows had a relatively light colour and mixed freely with the ambient seawater, whereas the
319 lower part of these flows was darker, denser, and undisturbed by the seawater (Figure 3C, D).
320 The flow front was more circular in vertical cross-section parallel to the flow direction than
321 for the low-density turbidity currents. The flows laden with 50%, 53% and 55% mud-grade
322 calcite lime-mud are classified as high-density turbidity currents (cf., Baker et al., 2017; Table
323 1).

324 The flow laden with 58% mud-grade calcite lime-mud had a characteristic lip at the top of the
325 head (white arrow in Figure 3E), The flow lacked internal mixing, and minor mixing with the
326 ambient water resulted in a dilute suspension cloud near the top of the flow. The head of the
327 58% flow had a pointed shape and was lifted off the floor of the tank by incursion of seawater

328 underneath the base of the flow, i.e., the flow hydroplaned. These characteristics match the
329 mud-flow type of Baker et al. (2017).

330 The flow laden with 59% mud-grade calcite lime-mud was wedge-shaped and it lacked internal
331 deformation. Mixing with the ambient seawater was negligible. The flow mobility was low
332 and most of the sediment was deposited close to the lock gate (Fig. 5). This flow is classified
333 as a slide (cf., Baker et al., 2017).

334 4.2 | Head velocity

335 Figure 4 shows how the head velocity of each mud-grade calcite lime-mud flow changed with
336 increasing distance, x , from the lock gate. The initial head velocity, at $x = 0.15$ m, increased
337 from 0.11 m s^{-1} for the 1% flow to 0.63 m s^{-1} for the 30% flow (Figure 4A) and then to 0.83 m
338 s^{-1} for the 45% flow (Figure 4B). As these low-density turbidity currents travelled along the
339 tank, their head velocity decreased to 0.053 m s^{-1} for the 1% flow, 0.39 m s^{-1} for the 30% flow
340 (Figure 4A), and 0.46 m s^{-1} for the 45% flow (Figure 4B). All $\leq 45\%$ flows reflected off the end
341 of the tank, so they had a minimum run-out distance of 4.69 m.

342 In contrast to the low-density turbidity currents, the initial head velocity decreased as the
343 lime-mud concentration of mud-grade calcite was increased from 50% to 59%: from 0.80 m
344 s^{-1} for the high-density turbidity current laden with 50% mud-grade calcite lime-mud via 0.55
345 m s^{-1} for the mud flow carrying 58% mud-grade calcite lime-mud to 0.44 m s^{-1} for the slide
346 laden with 59% mud-grade calcite lime-mud (Figure 4B). The 50% high-density turbidity
347 current decelerated quicker than the low-density turbidity currents near the end of tank but
348 still maintained a head velocity of 0.35 m s^{-1} close to the end wall. The 53% and 55% high-
349 density turbidity currents, 58% mud-grade calcite mud-flow, and 59% slide stopped before
350 reaching the end of the tank and did so progressively closer to the lock gate (Figure 4B). These
351 flows therefore had measurable run-out distances, decreasing from 3.75 m to 0.75 m, as the
352 lime-mud concentration of mud-grade calcite was increased (Table 2).

353 4.3 | Deposit properties

354 Figure 5 shows the deposits of all mud-grade calcite lime-mud flows that had a measurable
355 run-out distance. The length of the deposits decreased, and their maximum thickness
356 increased, as lime-mud concentrations of mud-grade calcite increased from 53% to 59%. The

357 53% high-density turbidity current produced a relatively thin deposit with a length of 3.75 m,
358 whereas the 59% slide produced a thick and short deposit that extended into the tank by only
359 0.75 m. The deposit shape of the high-density turbidity currents was different from that of
360 the mud flow and slide. The high-density turbidity current deposits thinned rapidly in the first
361 metre, after which the thickness was approximately constant for up to 3 m. The deposits then
362 terminated abruptly. The mud flow and slide deposits are characterised by more linear and
363 more rapid thinning than the high-density turbidity current deposits.

364

365 5 | DISCUSSION

366 5.1 | Is mud-grade calcite lime-mud cohesive?

367 Figure 6 depicts the maximum head velocity of the experimental flows as a function of lime-
368 mud-concentration of mud-grade calcite, and compares these with the strongly cohesive
369 bentonite clay, weakly cohesive kaolinite clay, and non-cohesive silica flour flows of Baker et
370 al. (2017). The maximum head velocity of the mud-grade calcite lime-mud-flows gradually
371 increased, as the initial suspended sediment concentration was increased from 1% to 45%,
372 because increasing the concentration of CaCO_3 increased the density contrast between the
373 flow and the ambient fluid; this excess density, together with turbulence, are the drivers of
374 these low-density turbidity currents. Despite the higher excess density in the mud-grade
375 calcite lime-mud-laden high-density turbidity currents, mud flow, and slide, the maximum
376 head velocity decreased rapidly as the sediment concentration was increased from 50% to
377 59% (Figure 6).

378 The shape of the maximum head velocity curve for mud-grade calcite lime-mud-matches that
379 of bentonite, kaolinite, and silica flour, but the mud-grade calcite lime-mud-curve is closest in
380 terms of maximum mobility, i.e., peak maximum head velocity, to the silica flour curve (Figure
381 6). This peak is at 45% for mud-grade calcite lime-mud-and at 47% for silica flour, whereas the
382 peaks for bentonite and kaolinite are at 16% and 22%, respectively. As silica flour is non-
383 cohesive, and kaolinite and bentonite are cohesive (Baker et al., 2017), this suggests that the
384 mud-grade calcite lime-mud-flows behaved in a non-cohesive manner and can reach
385 significantly higher mobilities at higher concentrations than cohesive clay flows (Figure 6). The
386 decrease in maximum head velocity between 50% and 59% mud-grade calcite lime-mud

387 therefore most likely results from attenuation of turbulence by frictional forces between the
388 CaCO_3 particles within the flow, rather than cohesive forces (which do not require particles
389 to 'rub' against each other). The fact that these concentrations are close to the random
390 packing density of spheres in deposits of 60% (loose random packing) to 64% (close random
391 packing), when a pervasive network of particle contacts is present and thus the frictional
392 strength is highest, supports this interpretation. The inference that the mud-grade calcite
393 ~~lime-mud~~-SGFs were non-cohesive, behaving in a similar way to the non-cohesive silica-flour
394 SGFs of Baker et al. (2017), is supported further by similar trends in run-out distance (Figure
395 7) and deposit shape (Figure 8). The bentonite and kaolinite clay flows started to run out and
396 change deposit shape at much lower concentrations than the silica-flour and mud-grade
397 calcite lime-mud-flows (Figure 7).

398 Figure 6 reveals also that the mud-grade calcite lime-mud-flows were more mobile than the
399 silica-flour flows at concentrations above c. 30%. The mud-grade calcite lime-mud-flows
400 reached a higher peak maximum head velocity than the silica-flour flows (0.85 m s^{-1} versus
401 0.75 m s^{-1}) and frictional forces slowed down the silica-flour flows at lower concentrations
402 than the mud-grade calcite lime-mud-flows. Moreover, matching run-out distances and
403 deposit shapes are associated with higher mud-grade calcite lime-mud-than silica-flour
404 concentrations in high-density turbidity currents, mud flows, and slides (Figure 7). This
405 confirms that the high-concentration, turbulence-attenuated, mud-grade calcite lime-mud
406 flows were more mobile than the silica-flour flows.

407 The comparison with Baker et al. (2017) in Figures 6–8 shows that the mud-grade calcite lime-
408 ~~mud~~-flows were non-cohesive, yet somewhat more mobile than non-cohesive silica-flour
409 flows under turbulence-attenuated conditions. Although silica flour was deemed to be non-
410 cohesive by Parker (1987), Pashley & Karaman (2004) suggested that silica-flour particles have
411 weak negative surface charges. Silica flour may therefore be weakly cohesive — but
412 considerably weaker than kaolinite — possibly explaining the lower mobility of silica-flour
413 laden high-density turbidity currents, mud flows and slides compared to the equivalent mud-
414 grade calcite lime-mud-flow types. However, this inferred higher mobility of mud-grade
415 calcite lime-mud-flows may be partly counteracted by the presence of weak surface charges
416 of CaCO_3 particles in electrolytic solutions, such as seawater (Eriksson et al., 2007).
417 Alternative explanations for the difference in mobility between the high-concentration silica-

418 flour and ~~mud-grade calcite lime-mud~~ SGFs are differences in median particle size (0.018 mm
419 and 0.009 mm, respectively), particle size distribution (poorly sorted and very poorly sorted,
420 respectively) and particle shape (e.g., Slooman et al., 2023). Further research is needed to
421 determine the effect of these parameters on differences in flow mobility for siliciclastic and
422 calciclastic sediment, especially in dense, turbulence-modulated flows.

423 5.2 | Wider implications

424 Our laboratory experiments provide a fundamental physical understanding of the dynamics
425 of SGFs that carry fine-grained CaCO₃. The experimental data suggest that these flows are
426 highly mobile up to concentrations that approach the packing density of deposits, because
427 ~~mud-grade calcite lime-mud~~ is physically non-cohesive and frictional forces are needed to
428 reduce flow mobility. Since the experiments isolated a single parameter, physical cohesion, a
429 detailed comparison with dynamically more complex natural SGFs on coral reefs is not
430 possible yet. Natural flows can be faster than the SGFs simulated herein, in which case the
431 changes in flow type, e.g., from low-density to high-density turbidity current, should occur at
432 even higher suspended sediment concentrations than found in this study. It is therefore
433 anticipated that, purely from the perspective of the lack of physical cohesion, ~~lime-mud~~
434 ~~laden~~ SGFs laden with mud-grade calcite on coral reefs are as effective in transporting
435 suspended sediment as in the experiments. This includes sediment eroded and resuspended
436 by storms and hurricanes and sediment made available by slope failures on oversteepened
437 reef fronts and forereefs. The latter process is facilitated by the usually steep seaward slope
438 gradient of coral reefs. Like in non-carbonate environments, relatively low-concentration
439 turbidity currents of high mobility are more likely to occur than hyperconcentrated (more
440 than 50% by volume of suspended sediment) turbulence-suppressed mud flows and slides of
441 low mobility on and around coral reefs. However, there are conditions in which low-mobility
442 flows might form. Natural SGFs can be highly stratified, with suspended sediment
443 concentrations significantly greater near the bottom of the flow than near the top, e.g., for
444 siliciclastic flows in the Congo Canyon (Azpiroz-Zabala et al., 2017), which may take equivalent
445 calciclastic SGFs on coral reefs into the non-turbulent, frictional regime near the seabed.
446 Moreover, failure of unstable slopes — particularly involving ‘en masse’ erosion by, for
447 example, delamination (Eggenhuisen et al., 2011) — may initiate mud flows or slides.
448 Notwithstanding these conditions, the lack of physical cohesion should promote the transport

449 of suspended fine-grained CaCO_3 away from reefs by SGFs and thus the efficiency of cleansing
450 turbid water after storms, so more light is available for photosynthesis. This removal of
451 suspended sediment is likely to be even more effective above unhealthy reefs than above
452 healthy reefs, because the increased volume of biologically produced mud-grade calcite lime
453 ~~mud~~-on unhealthy, brittle reefs (MacDonald & Perry, 2003; Perry et al., 2015; Russ et al.,
454 2015), as well as the greater potential for sediment erosion during storms, are expected to
455 increase the suspended sediment concentration and thus the excess density and mobility of
456 SGFs.

457 However, physical cohesion is not the only parameter that controls the mobility of CaCO_3 -
458 laden SGFs. Biological cohesion associated with 'sticky' extracellular polymeric substances
459 (EPS) produced by microphytobenthos, bacteria and other micro-organisms, has been found
460 to reduce the mobility of SGFs at concentrations that are several orders of magnitude lower
461 than for physically cohesive, siliciclastic clay (Craig et al., 2020; Sobocinska & Baas, 2022).
462 Coral reefs are characterised by a large species richness and diversity and carbonate grains
463 coated in organic matter are common (e.g., Schieber et al., 2013). It is therefore likely that
464 EPS hinder the removal of suspended sediment by SGFs from reefs by increasing the cohesive
465 forces and attenuating the turbulent driving forces, especially in high-density turbidity
466 currents. On unhealthy reefs, microbial films and algae grow rapidly, outcompeting corals for
467 space (Tanner, 1995; Lirman, 2001; Barott et al., 2011), and producing large volumes of EPS.
468 This is postulated to further reduce the mobility of SGFs above and around unhealthy reefs
469 and thus reduce their ability to transport suspended sediment away from reefs compared to
470 healthy reefs. This reduced mobility on unhealthy reefs would work against the increased
471 mobility by the lack of physical cohesion, inferred above. Despite the conceivable reduction
472 in SGF mobility by biological cohesion, Hubbard (1986) showed that 1/3 to 1/2 of the annual
473 offshore sediment flux can be reached during merely two weeks of stormy weather. This
474 supports the strong influence of physical conditions on offshore sediment transport in
475 carbonate environments.

476 In addition to biological cohesion, particle shape and density also need to be considered in
477 assessing the mobility of CaCO_3 -laden SGFs and their ability to clean turbid water (de Kruijff et
478 al., 2021; Bian et al., 2023). The mud-grade calcite lime ~~mud~~-used in the present experiments
479 is not ideal for studying these parameters, as it consists of finely powdered limestone that is

480 suitable for understanding the basic physical properties of ~~mud-grade calcite lime-mud~~ SGFs,
481 but it may not represent the perceived compositional and textural variability of natural flows.
482 Although the density of CaCO_3 is comparable to that of quartz-rich siliciclastic sediment, the
483 true density of carbonate particles in natural environments is controlled by the internal
484 porosity of bioclasts; most bioclasts have a density below 2710 kg m^{-3} . The shape of bioclasts
485 is also more variable than the shape of siliciclastic particles. Whereas siliciclastic particles
486 usually approach a spherical shape, the shape of bioclastic particles ranges from spherical for
487 ooids to highly irregular, depending on the shape of shells, skeletons, and other hard parts of
488 calcifying organisms, as well as fragments thereof (de Kruijf et al. (2021). Moreover, mud to
489 silt-grade carbonate produced in tropical reef environments is excreted by fish (Salter et al.,
490 2012) and may have a range of shapes as well as disaggregation potential (Perry et al., 2011).
491 Based on detailed laboratory experiments, Slooman et al. (2023) showed that natural non-
492 spheroidal skeletal carbonate sand generally has a lower settling velocity than spheroidal
493 sand. This implies that SGFs laden with non-spherical carbonate sand have a higher mobility
494 than SGFs with spherical sand, especially if the sand particles are porous. However, further
495 research is needed to verify if the results of Slooman et al. (2023) extend to SGFs laden with
496 fine-grained, clay and silt-sized, CaCO_3 .

497 The benefits of the perceived highly mobile nature of ~~lime-mud laden~~ SGFs laden with mud-
498 grade calcite may extend beyond the cleansing of turbid water above shallow-water reefs that
499 depend primarily on photosynthesis. Deep-water reefs, including reefs in canyons, exist in the
500 mesophotic zone (30-150 m) (Lesser et al., 2009), where removing suspended sediment is not
501 as vital as for shallow-water reefs. Deep-water reefs rely less on sunlight for photosynthesis
502 and more on nutrient supply via heterotrophy rather than autotrophy (Mass et al., 2007).
503 Hence, the high mobility of ~~mud-grade calcite lime-mud~~ SGFs makes them effective as export
504 systems of sediment from shallow-water reefs, and also as import systems of nutrients to
505 deep-water reefs. Given the recently discovered common occurrence of SGFs (e.g., Azpiroz-
506 Zabala et al., 2017) and other types of currents, such as tidal currents, in canyons, this process
507 of nutrient supply to deep-water reefs may be more important than realised up to now, and
508 therefore add to better known nutrient sources of pelagic and deep-water bottom-current
509 origin.

510

511 6 | CONCLUSIONS

512 The present experimental research reveals that ~~lime-mud-laden~~ SGFs laden with mud-grade
513 calcite are non-cohesive and behave in a similar way to SGFs laden with non-cohesive
514 siliciclastic fine silt. Both flow types remain fully turbulent and highly mobile up to
515 concentrations that approach that of randomly packed deposits, reflected in similar
516 maximum head velocity curves and suspended-sediment-concentration controlled run-out
517 distances and deposit thicknesses. Reduced mobility in hyperconcentrated mud-grade calcite
518 ~~lime-mud~~ SGFs involves frictional forces, which require particles to be close enough to rub
519 against each other and thereby take forward energy out of the flow. However, the 50% or
520 more of fine CaCO₃ required for frictional forces to become effective are less likely to occur
521 in nature than the lower concentrations at which turbulent forces dominate mud-grade
522 calcite ~~lime-mud~~ flows. It is therefore concluded that, purely from the perspective of the lack
523 of physical cohesion, mud-grade calcite ~~lime-mud~~ SGFs should be highly effective in moving
524 suspended sediment away from shallow-water reefs, especially if a slope is present, such as
525 on the reef front and foreereef.

526 This study provides a platform for further increases in the understanding of SGFs laden with
527 fine CaCO₃ by incorporating the influence of biological cohesion, particle density, and particle
528 shape on the sediment transport dynamics of SGFs above and around coral reefs and in other
529 carbonate environments. Given the high ecological, economic, and societal importance of
530 coral reefs and the threat imposed on reefs by anthropogenic climate change, a redressing of
531 the balance between studies of siliciclastic and calciclastic SGFs in favour of calciclastic SGFs
532 and their deposits is timely.

533

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537 ~~construction of the lock-exchange tank in the School of Ocean Sciences, Bangor University, as~~
538 ~~well as the purchase of materials. Rob Evans was instrumental in designing and~~
539 ~~commissioning this facility. The authors have no conflicts of interest to declare.~~

540

541 **DATA AVAILABILITY STATEMENT**

542 The data that support the findings of this study are available from the corresponding author upon
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551

552 **AUTHORS' CONTRIBUTIONS**

553 WH performed the laboratory experiments, did the data analysis and wrote the first draft of the paper.
554 JHB, SL and JH initiated the research, supervised the experiments and data analysis, and wrote the
555 final version of this paper.

556

557 **CONFLICT OF INTEREST STATEMENT**

558 The authors have no conflict of interest to declare.

559

560 **DATA AVAILABILITY STATEMENT**

561 The data that support the findings of this study are available from the corresponding author upon
562 reasonable request.

563

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565 **REFERENCES**

- 566 Anthony, K.R.N., Kline, D.I., Diaz-Pulido, G., Dove, S. & Hoegh-Guldberg, O. (2008) Ocean acidification causes
567 bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of*
568 *the United States of America*, 105(45), 17442–17446.
- 569 Austin, J., Schlager, W. & Palmer, A (1986) Leg 101: Proceedings Initial Reports (Pt. A). Ocean Drilling Program,
570 College Station, Texas.
- 571 Azpiroz-Zabala, M., Cartingy, M.J.B., Talling, P.J., Parsons, D.R., Sumner, E.J., Clare, M.A., Simmons, S.M., Cooper,
572 C. & Pope, E.L. (2017) Newly recognized turbidity current structure can explain prolonged flushing of
573 submarine canyons. *Science Advances*, 3, e1700200.
- 574 Baas, J.H. & Best, J.L. (2002) Turbulence modulation in clay-rich sediment-laden flows and some implications for
575 sediment deposition. *Journal of Sedimentary Research*, 72, 336–340.
- 576 Baas, J.H., Best, J.L. & Peakall, J. (2011) Depositional processes, bedform development and hybrid bed formation
577 in rapidly decelerated cohesive (mud–sand) sediment flows. *Sedimentology*, 58, 1953–1987.
- 578 Baas, J.H., Best, J.L., Peakall, J. & Wang, M. (2009) A phase diagram for turbulent, transitional, and laminar clay
579 suspension flows. *Journal of Sedimentary Research*, 79, 162–183.
- 580 Baker, M.L., & Baas, J.H. (2023) Does sand promote or hinder the mobility of cohesive sediment gravity flows?
581 *Sedimentology*, 70, 1110–1130.
- 582 Baker, M.L., Baas, J.H. & Malarkey, J. (2017) The effect of clay type on the properties of cohesive sediment gravity
583 flows and their deposits. *Journal of Sedimentary Research*, 87, 1176–1195.
- 584 Barott, K.L., Rodriguez-Mueller, B., Youle, M., Marhaver, K.L., Vermeij, M.J.A., Smith, J.E. & Rohwer, F.L. (2011)
585 Microbial to reef scale interactions between the reef-building coral *Montastraea annularis* and benthic
586 algae. *Proceedings of the Royal Society B: Biological Sciences*, 279, 1655–1664.
- 587 Berkelmans, R. & van Oppen, M.J.H. (2006) The role of zooxanthellae in the thermal tolerance of corals: a ‘nugget
588 of hope’ for coral reefs in an era of climate change. *Proceedings of the Royal Society B*, 273, 2305–2312.
- 589 Betzler, C., Eberli, G.P. & Alvarez Zarikian, C.A. (2017). Maldives monsoon and sea level. *Proceedings of the*
590 *International Ocean Discovery Program*, 359, College Station, Texas.
- 591 Bian, C., Chen, J., Jiang, C., Wu, Z. & Yao, Z. (2023) Threshold of motion of coral sediment under currents in flume
592 experiments. *Sedimentology*, 70, 1723–1740.
- 593 Brodie, J. & Pearson, R.G. (2016) Ecosystem health of the Great Barrier Reef: Time for effective management
594 action based on evidence. *Estuarine, Coastal and Shelf Science*, 183, 438–451.
- 595 Brunner, C.A. (2021) Climate change doubles sedimentation-induced coral recruit mortality. *Science of the Total*
596 *Environment*, 768, 143897.

- 597 [Chazottes, V., Reijmer, J.J.G. & Cordier, E. \(2008\) Sediment characteristics in reef areas influenced by](#)
598 [eutrophication-related alterations of benthic communities and bioerosion processes. *Marine Geology*, 250,](#)
599 [114–127.](#)
- 600 Cinner, J. (2014) Coral reef livelihoods. *Current Opinion in Environmental Sustainability*, 7, 65–71.
- 601 Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S. & Turner, R.K.
602 (2014) Changes in the global value of ecosystem services. *Global Environmental Change*, 26, 152–158.
- 603 Craig, M.J., Baas, J.H., Amos, K.J., Strachan, L.J., Manning, A.J., Paterson, D.M., Hope, J.A., Nodder, S.D. & Baker,
604 M.L. (2020) Biomediation of submarine sediment gravity flow dynamics. *Geology*, 48, 72–76.
- 605 Crook, E.D., Cohen, A.L., Rebolledo-Vieyra, M., Hernandez, L & Paytan, A. (2013) Reduced calcification and lack
606 of acclimatization by coral colonies growing in areas of persistent natural acidification. *PNAS*, 110, 11044–
607 11049.
- 608 de Kruijf, M., Slootman, A., de Boer, R.A. & Reijmer, J.J.G. (2021) On the settling of marine carbonate grains:
609 Review and challenges. *Earth-Science Reviews*, 217, 103532.
- 610 Dyer, K.R. & Manning, A.J. (1999) Observation of the size, settling velocity and effective density of flocs, and
611 their fractal dimensions. *Journal of Sea Research*, 41, 87–95.
- 612 Eberli, G.P. (1987) Carbonate turbidite sequences deposited in rift-basins of the Jurassic Tethys Ocean (eastern
613 Alps, Switzerland). *Sedimentology*, 34, 363–388.
- 614 Eberli, G.P., Swart, P.K. & Malone, M.J. (1997) *Proceedings Ocean Drilling Program, Initial Reports, Leg 166*,
615 College Station, Texas, p. 850.
- 616 Eggenhuisen, J.T., McCaffrey, W.D., Haughton, P.D.W. & Butler, R.W.H. (2011) Shallow erosion beneath turbidity
617 currents and its impact on the architectural development of turbidite sheet systems. *Sedimentology*, 58,
618 936–959.
- 619 Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W. & Todd, P.A. (2012) Environmental impacts of dredging and other
620 sediment disturbances on corals: A review. *Marine Pollution Bulletin*, 64, 1737–1765.
- 621 Eriksson, R., Merta, J. & Rosenholm, J.B. (2007) The calcite/water interface: I. Surface charge in indifferent
622 electrolyte media and the influence of low-molecular-weight polyelectrolyte. *Journal of Colloid and*
623 *Interface Science*, 313, 184–193.
- 624 Evans, R.D., Wilson, S.K., Fisher, R., Ryan, N.M., Babcock, R., Blakeway, D., Bond, T., Dorji, P., Dufois, F., Fearn,
625 P., Lowe, R.J., Stoddart, J. & Thomson, D.P. (2020) Early recovery dynamics of turbid coral reefs after
626 recurring bleaching events. *Journal of Environmental Management*, 268, 110666.
- 627 Folk, R.L. & Ward W.C. (1957) Brazos river bar: A study in the significance of grain size parameters. *Journal of*
628 *Sedimentary Petrology*, 27, 3–26.

- 629 Gattuso, J.P., Allemand, D. & Frankignoulle, M. (1999) Photosynthesis and calcification at cellular, organismal
630 and community levels in coral reefs: A review on interactions and control by carbonate chemistry. *American*
631 *Zoologist*, 39, 160–183.
- 632 Haak, A.B. & Schlager, W. (1989) Compositional variations in calciturbidites due to sea-level fluctuations, late
633 Quaternary, Bahamas. *Geologische Rundschau*, 78, 477–486.
- 634 Hodson, J.M. & Alexander, J. (2010) The effects of grain density variation on turbidity currents and some
635 implications for the deposition of carbonate turbidites. *Journal of Sedimentary Research*, 80, 515–528.
- 636 Hubbard, D.K. (1986) Sedimentation as a control of reef development: St. Croix, U.S.V.I. *Coral Reefs*, 5, 117–125.
- 637 Hubbard, D.K., Miller, A.I. & Scaturro, D. (1990) Production and cycling of calcium carbonate in a shelf-edge reef
638 system (St. Croix, US Virgin Islands); Applications to the nature of reef systems in the fossil record. *Journal*
639 *of Sedimentary Petrology*, 60, 335–360.
- 640 Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen,
641 M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.-P.A., Hoey,
642 A.S., Hoogenboom, M., Lowe, R.J., McCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G. &
643 Wilson, S.K. (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*,
644 359, 80–83.
- 645 Jones, R., Giofre, N., Luter, H.M., Neoh, T.L., Fisher, R. & Duckworth, A. (2020) Responses of corals to chronic
646 turbidity. *Scientific Reports*, 10, 4762.
- 647 Kneller, B. & Buckee, C. (2000) The structure and fluid mechanics of turbidity currents: a review of some recent
648 studies and their geological implications. *Sedimentology*, 47, 62–94.
- 649 Langdon, C. & Atkinson, M.J. (2005) Effect of elevated pCO₂ on photosynthesis and calcification of corals and
650 interactions with seasonal change in temperature/irradiance and nutrient enrichment. *Journal of*
651 *Geophysical Research: Oceans*, 110, C09S07.
- 652 Lesser, M.P., Slattery, M. & Leichter, J.J. (2009) Ecology of mesophotic coral reefs. *Journal of Experimental*
653 *Marine Biology and Ecology*, 375, 1–8.
- 654 Lirman, D. (2001) Competition between macroalgae and corals: Effects of herbivore exclusion and increased
655 algal biomass on coral survivorship and growth. *Coral Reefs*, 19, 392–399.
- 656 Liu, G., Wang, D., Chen, W., Wang, W., Betzler, C. & Han, X. (2023) Submarine landslides on a carbonate platform
657 slope changing transport pathways of deepwater gravity flows: Insights from the Xisha Islands, South China
658 Sea. *Geomorphology*, 437, 108813.
- 659 Lokier, S.W. (2023) Marine carbonate sedimentation in volcanic settings. In: Di Capua, A., De Rosa, R., Kereszturi,
660 G., Le Pera, E., Rosi, M. & Watt, S.F.L. (Eds) *Volcanic processes in the sedimentary record: When volcanoes*
661 *meet the environment*, Geological Society, [London](#), Special Publication, 520, 547–594.

- 662 Lokier, S.W., Wilson, M.E.J. & Burton, L.M. (2009) Marine biota response to clastic sediment influx: A quantitative
663 approach. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 281, 25–42.
- 664 Lopez-Gamundi, C., Barnes, B.B., Bakker, A.C., Harris, P., Eberli, G.P. & Purkis, S.J. (2024) Spatial, seasonal, and
665 climatic drivers of suspended sediment atop Great Bahama Bank. *Sedimentology*, 71, 769–792.
- 666 MacDonald, I.A. & Perry, C.T. (2003) Biological degradation of coral framework in a turbid lagoon environment,
667 Discovery Bay, north Jamaica. *Coral Reefs*, 22, 523–535.
- 668 Mallela, J. & Perry, C.T. (2006) Calcium carbonate budgets for two coral reefs affected by different terrestrial
669 runoff regimes, Rio Bueno, Jamaica. *Coral Reefs*, 26, 129–145.
- 670 Marr, J.G., Harff, P.A., Shanmugam, G. & Parker, G. (2001) Experiments on subaqueous sandy gravity flows: The
671 role of clay and water content in flow dynamics and depositional structures. *Geological Society of America*
672 *Bulletin*, 113, 1377–1386.
- 673 Mass, T., Einbinder, S., Brokovich, E., Shashar, N., Vago, R., Erez, J. & Dubinsky, Z. (2007) Photoacclimation of
674 *Stylophora pistillata* to light extremes: metabolism and calcification. *Marine Ecology Progress Series*, 334,
675 93–102.
- 676 Mehta, A.J., Hayter, E.J., Parker, R., Krone, R.B. & Teeter, A.M. (1989) Cohesive sediment transport. 1: Process
677 description. *Journal of Hydraulic Engineering*, 115, 1076–1093.
- 678 Middleton, G.V. & Hampton, M.A. (1973) Part 1. Sediment gravity flows: Mechanics of flow and deposition. In:
679 Middleton, G.V. & Bouma, A.A. (Eds) *Turbidites and deep-water sedimentation*, SEPM Pacific Section Short
680 Course Notes, Anaheim, California, p. 38.
- 681 Mohrig, D. & Marr, J.G. (2003) Constraining the efficiency of turbidity current generation from submarine debris
682 flows and slides using laboratory experiments. *Marine and Petroleum Geology*, 20, 883–899.
- 683 Mulder, T. & Alexander, J. (2001) The physical character of subaqueous sedimentary density flow and their
684 deposits. *Sedimentology*, 48, 269–299.
- 685 Parker, G. (1987) Experiments on turbidity currents over an erodible bed. *Journal of Hydraulic Research*, 25, 123–
686 147.
- 687 Pashley, R.M. & Karaman, M.E. (2004) *Applied Colloid and Surface Chemistry*. London: John Wiley & Sons, p. 188.
- 688 Payros, A. & Pujalte, V. (2008) Calciclastic submarine fans: An integrated overview. *Earth-Science Reviews*, 86,
689 203–246.
- 690 Perry, C.T., Salter, M.A., Harborne, A.R., Crowley, S.F., Jelks, H.L. & Wilson, R.W. (2011) Fish as major carbonate
691 mud producers and missing components of the carbonate factory. *Proceedings of the National Academy of*
692 *Sciences*, 108, 3865–3869.

- 693 Perry, C.T., Kench, P.S., O'Leary, M.J., Morgan, K.M. & Januchowski-Hartley, F. (2015) Linking reef ecology to
694 island building: Parrotfish identified as major producers of island-building sediment in the Maldives.
695 *Geology*, 43, 503–506.
- 696 Postma, G. (2011) Sediment gravity flow. In: Singh, V.P., Singh, P. & Haritashya, U.K. (Eds), *Encyclopedia of snow,*
697 *ice and glaciers*, Geology Faculty Publications, Paper 7, University of Dayton, Ohio, 1005–1010.
- 698 Reijmer, J.J.G., Palmieri, P. & Groen, R. (2012) Compositional variations in calciturbidites and calcidebrites in
699 response to sea-level fluctuations (Exuma Sound, Bahamas). *Facies*, 58, 493–507.
- 700 Reijmer, J.J.G., Schlager, W., Bosscher, H., Beets, C.J. & McNeill, D.F. (1992) Pliocene/Pleistocene platform facies
701 transition recorded in calciturbidites (Exuma Sound, Bahamas). *Sedimentary Geology*, 78, 171–179.
- 702 Rogers, C.S. & Ramos-Scharrón, C.E. (2022) Assessing effects of sediment delivery to coral reefs: A Caribbean
703 watershed perspective. *Frontiers in Marine Science*, 8, 773968.
- 704 Rogers, C.S. (1990) Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress*
705 *Series*, 62, 185–202.
- 706 Russ, G.R., Questel, S.L.A., Rizzari, J.R. & Alcalá, A.C. (2015) The parrotfish–coral relationship: Refuting the
707 ubiquity of a prevailing paradigm. *Marine Biology*, 162, 2029–2045.
- 708 [Salter, M.A., Perry, C.T. & Wilson, R.W. \(2012\) Production of mud-grade carbonates by marine fish: Crystalline](#)
709 [products and their sedimentary significance. *Sedimentology*, 59, 2172–2198.](#)
- 710 Schieber, J., Southard, J.B., Kissling, P., Rossman, B. & Ginsburg, R. (2013) Experimental deposition of carbonate
711 mud from moving suspensions: Importance of flocculation and implications for modern and ancient
712 carbonate mud deposition. *Journal of Sedimentary Research*, 83, 1025–1031.
- 713 Scoffin, T. (1993) The geological effects of hurricanes on coral reefs and the interpretation of storm deposits.
714 *Coral Reefs*, 12, 203–221.
- 715 Sheppard, C., Davy, S., Pilling, G. & Graham, N. (2017) *The Biology of Coral Reefs*. Oxford: Oxford University Press,
716 p. 384.
- 717 Sloom, A., de Kruijf, M., Glatz, G., Eggenhuisen, J.T., Zühlke, R. & Reijmer, J.J.G. (2023) Shape-dependent
718 settling velocity of skeletal carbonate grains: Implications for calciturbidites. *Sedimentology*, 70, 1683–
719 1722.
- 720 Sobocinska, A. & Baas, J.H. (2022) Effect of biological polymers on mobility and run-out distance of cohesive and
721 non-cohesive sediment gravity flows. *Marine Geology*, 452, 106904.
- 722 Spalding, M.D. (2001) *World Atlas of Coral Reefs*. California: University of California Press, p. 424.

- 723 Spalding, M.D, Ruffo, S., Lacambra, C., Meliane, I., Hale, L., Shepard, C.C. & Beck, M.W. (2014) The role of
724 ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean & Coastal*
725 *Management*, 90, 50–57.
- 726 Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley,
727 P.M. (2013) *Climate change 2013: The physical science basis. Contribution of working group I to the fifth*
728 *assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press,
729 Cambridge, United Kingdom and New York, NY, USA, p. 1535.
- 730 Sumner, E.J., Talling, P.J. & Amy, L.A. (2009) Deposits of flows transitional between turbidity current and debris
731 flow. *Geology*, 37, 991–994.
- 732 Swart, P.K., Eberli, G.P., Malone, M.J. & Sarg, J.F. (2000) *Proceedings Ocean Drilling Program, Leg 166, Scientific*
733 *Results*, College Station, Texas, p. 213.
- 734 Talling, P.J. (2014) On the triggers, resulting flow types and frequencies of subaqueous sediment density flows
735 in different settings. *Marine Geology*, 352, 155–182.
- 736 Talling, P.J., Allin, J., Armitage, D.A., Arnott, R.W.C., Cartigny, M.J.B., Clare, M.A., Felletti, F., Covault, J.A.,
737 Girardclos, S., Hansen, E., Hill, P.R., Hiscott, R.N., Hogg, A.J., Clarke, J.H., Jobe, Z.R., Malgesini, G., Mozzato,
738 A., Naruse, H., Parkinson, S., Peel, F.J., Piper, D.J.W., Pope, E., Postma, G., Rowley, P., Sguazzini, A.,
739 Stevenson, C.J., Sumner, E.J., Sylvester, Z., Watts, C. & Xu, J. (2015) Key future directions for research on
740 turbidity currents and their deposits. *Journal of Sedimentary Research*, 85, 153–169.
- 741 Talling, P.J., Masson, D.G., Sumner, E.J. & Malgesini, G., 2012, Subaqueous sediment density flows: Depositional
742 processes and deposit types. *Sedimentology*, 59, 1937–2003.
- 743 Tanner, J.E. (1995) Competition between scleractinian corals and macroalgae: An experimental investigation of
744 coral growth, survival and reproduction. *Journal of Experimental Marine Biology and Ecology*, 190, 151–
745 168.
- 746 Trower, E.J., Lamb, M.P. & Fischer, W.W. (2019) The origin of carbonate mud. *Geophysical Research Letters*, 46,
747 2696–2703.
- 748 Tuttle, L.J. & Donahue, M.J. (2022) Effects of sediment exposure on corals: A systematic review of experimental
749 studies. *Environmental Evidence*, 11:4, 33 p.
- 750 Venn, A.A., Tambutté, E., Caminiti-Segonds, N., Techer, N., Allemand, D. & Tambutté, S. (2019) Effects of light
751 and darkness on pH regulation in three coral species exposed to seawater acidification. *Scientific Reports*,
752 9, 2201.
- 753 Wilson, M.E.J. (2012) Equatorial carbonates: An earth systems approach. *Sedimentology*, 59, 1–31.

754 **TABLE AND FIGURE CAPTIONS**

755 TABLE 1 Generic sediment gravity flow type classification scheme of Baker & Baas (2023)
756 applied to the CaCO₃-laden flows used in this study (modified after Baker & Baas, 2023)

757 TABLE 2 Summary of experimental data of this study (mud-grade calcite lime mud) and
758 Baker et al. (2017) (kaolinite, bentonite, silica flour)

759 FIGURE 1 Experimental setup used for the lock-exchange tank experiments. The tank is 0.2
760 m wide and the slope of the tank was set to 0° in all experiments (after Baker et al. 2017)

761 FIGURE 2 Frequency distribution curve of the particle size of the mud-grade calcite lime
762 mud-used in the experiments. Particle size is given in ϕ (phi)-values

763 FIGURE 3 Video stills of the heads of selected CaCO₃ flows. (A) 15% low-density turbidity
764 current, (B) 25% low-density turbidity current, (C) 53% high-density turbidity current, (D) 55%
765 high-density turbidity current, (E) 58% mud flow, and (F) 59% slide. Dashed lines in (C) and (D)
766 show density interfaces in high-density turbidity currents. Arrow in (E) points to lip region of
767 mud flow. Scale bar is 100 mm long

768 FIGURE 4 Head velocity against downflow distance from the lock gate for: (A) 1% to 30%
769 mud-grade calcite lime mud flows; and (B) 35% to 59% mud-grade calcite lime mud flows.
770 Low-density turbidity currents, high-density turbidity currents, mud flows, and slides are
771 given in blue, green, red, and black, respectively

772 FIGURE 5 Deposit thickness trends of mud-grade calcite lime mud flows that had a
773 measurable run-out distance. High-density turbidity currents, mud flow, and slide are given
774 in green, red, and black, respectively

775 FIGURE 6 Maximum head velocity of CaCO₃, kaolinite, bentonite, and silica flour flows
776 against initial suspended sediment concentration

777 FIGURE 7 Run-out distance of CaCO₃, kaolinite, bentonite, and silica flour flows against
778 initial suspended sediment concentration. Run-out distances of 4.69 m denote minimum
779 values; these flows reflected off the end of the tank

780 FIGURE 8 Deposit thickness trends of mud-grade calcite ~~lime-mud~~ and silica-flour flows
781 against downflow distance from the lock gate, comparing selected high-density turbidity
782 currents (HDTCs), mud flows, and slides from this study and Baker et al. (2017)

For Review Only

Reviewer comments (Slootman)

The text has been clarified and reads very well. Section 2 Background and Rationale is long but necessary. Figures are clear and easy to follow. The Authors have considered all issues brought up during the first round of review, as very clearly documented in the review materials. Thank you. (Although I don't agree with the Authors' reply on Q2.13, that readers do not need a reminder of the size limits of sand, silt and clay as expressed in the phi-scale, but that is the Authors' choice.)

We thank the reviewer again for his positive assessment of our manuscript. We address his latest comments below, and have acted upon these accordingly.

Yet, some issues remain with respect to the generally applicability of the findings presented here. The main issue some carbonate researchers may have to be convinced of, in order for them to accept the experiments as analogue processes to the modern world, is how well the lime mud used in the experiments compares to natural lime mud. I suggest to be careful in making the statements too general, as crushed calcite may be applicable only to a limited subset of carbonate mud. Some detailed concerns and suggestions below.

Crushed carbonate is an analogue to lime mud, but only in specific environments. There are other lime muds too with different particle shape and cohesiveness.

The present manuscript in its revised form is a valuable contribution to the understanding of transport and depositional processes in the carbonate realm with respect to non-cohesive lime mud mobility. I have discussed some of the findings and reasonings in the manuscript with my more senior peers. I noticed that an issue that keeps returning to the table is that "crushed carbonate is not analogue to lime mud" because of the (typical) cohesiveness of lime mud and the non-cohesiveness of the crushed carbonate. This may be a valid point when considering lime mud deposits in all environments of the carbonate platform-slope-basin realm. However, the Authors do not claim, in my understanding, that the used crushed carbonate in the experiments is representative for all lime mud. The experiments deal with the specific setting of fine-grained sediment in the reef environment, which may smother – and eventually kill – corals. This lime mud in the reef environment is of detrital origin formed by abrasion during high-energy events (L150-152), biological erosion by nibbling fish and urchins (L85- 86), and anthropogenic remobilisation by fishing and dredging (L155-156).

Echoing some of the concern that came up during a heated discussion with my more senior peers: it is problematic then, if the results are presented as if applicable to all carbonate mud. For example in L34 of the abstract: "Fine CaCO₃ gravity flows can therefore be regarded as non-cohesive..." and in Section 5.1 of the Discussion "Is lime mud cohesive?" in L348, to which the Authors answer with "no". A general statement as in L405: "lime mud is physically non-cohesive", is in disagreement with the literature. See for example:

- Kenter, J.A.M. and Schlager, W. (1989) A comparison of shear strength in calcareous and siliciclastic marine sediments. *Marine Geology*, 88, 145-152.
- Kenter, J.A.M. (1990) Carbonate platform flanks: slope angle and sediment fabric. *Sedimentology*, 37, 777-794.
- Kenter, J.A.M. (1990) Geometry and declivity of submarine slopes. Ph.D., Vrije Universiteit, Faculty of Earth Sciences, Amsterdam, 128 pp.

The Authors tested a very specific type of lime mud: crushed calcite. In Figure 6, two types of siliciclastic clay minerals and non-cohesive silica flower (=crushed quartz) are specified, but only one carbonate 'mud' is represented by non-cohesive carbonate flower (=crushed calcite). This is likely an underrepresentation of the suite of lime muds in the modern world (e.g., aragonite needles). There are numerous ways to produce lime mud: e.g., fish excrements, green algae, whiting, algal mats, and physical abrasion. Some papers that deal with different lime mud types:

- Macintyre, I.G. and Reid, R.P. (1992) Comment on the origin of aragonite needle mud: a picture is worth a thousand words. *Journal of Sedimentary Petrology*, 62, 1095-1097.
- Salter, M.A., Perry, C.T. and Wilson, R.W. (2012) Production of mud-grade carbonates by marine fish: Crystalline products and their sedimentary significance. *Sedimentology*, 59, 2172-2198.
- Lopez-Gamundi, C., Barnes, B.B., Bakker, A.C., Harris, P., Eberli, G.P. and Purkis, S.J. (2024) Spatial, seasonal and climatic drivers of suspended sediment atop Great Bahama Bank. *Sedimentology*, 71, 769-792.
- Lopez-Gamundi, C., Dobbelaere, T., Hanert, E., Harris, P.M., Eberli, G. and Purkis, S.J. (2022) Simulating sedimentation on the Great Bahama Bank – Sources, sinks and storms. *Sedimentology*, 69, 2693-2714.

The reviewer may have overlooked our definition of lime mud given in the introductory chapter: "Below, the term 'lime mud' is used to describe this sediment in a purely granulometric sense, i.e., a mixture of silt and clay-sized CaCO₃ particles, without reference to a specific physical, biological or chemical origin". We also discussed in Section 5.2 that, although physical (i.e. non-biological) cohesion is absent, biological cohesion and physical parameters like particle shape and density, will complicate the application of our results to natural environments. However, it should be realised that our work started with the simplest end-member analogue of a potential spectrum of natural lime muds, which any good analogue modelling study should do. We thus isolated a single variable and provide a starting point for studying other variables (i.e using a bottom-up approach), with key

variables discussed in Section 5. Yet, in order to remove any potential confusion in the use of 'lime mud', we now use the term 'mud-grade calcite' in the revised text.

Regarding "*Fine CaCO₃ gravity flows can therefore be regarded as non-cohesive...*", the key is in the term 'physical', which the reviewer chose to remove. This term excludes biologically cohesive mud, which is emphasised as a complicating factor in the last part of the abstract, and now highlighted better: "*However, biological cohesion, caused by 'sticky' extracellular polymer substances produced by micro-organisms, can render mud-grade calcite cohesive and sediment gravity flows less mobile*" (Lines 37–39). The discussion takes this further by devoting almost two pages to cohesion of biological origin, and also particle shape and density. We feel that expanding this further would risk making the discussion too speculative.

We have also added a 4th aim at the end of the introduction to emphasise that we discuss biological cohesion and particle shape and density in our paper: "*... to consider the potential effect of biological cohesion and particle shape and density on the mobility of SGFs laden with mud-grade calcite in view of future research*" (Lines 119–120).

We hope that we have now done enough to convince the reviewer that we are aware that natural processes and environments are more complex than laboratory experiments can simulate straightforwardly; we therefore need to take a stepwise approach to improve understanding of the dynamics of calcareous gravity flows.

How about density cascading?

Have the Authors considered density cascading as an alternative to sediment-gravity flows for the removal of mud-grade sediment from the reef? See for example:

- Wilson, P.A. and Roberts, H.H. (1992) Carbonate-periplatform sedimentation by density flows: a mechanism for rapid off-bank and vertical transport of shallow-water fines. *Geology*, 20, 713-716.
- Wilson, P.A. and Roberts, H.H. (1995) Density cascading: off-shelf sediment transport, evidence and implications, Bahama Banks. *Journal of Sedimentary Research*, A65, 45-56.

We feel this is beyond the scope of the paper. Density cascading refers to a specific type of sediment gravity flow. We do not see the benefit of referring to this flow type — or any specific sediment gravity flow types other than turbidity current and mud flow — in this manuscript, as it will divert from the main message.

Some other references

Additional work dealing with sediment production within carbonate reef systems that might be worth considering:

- Chazottes, V., Le Campion-Alsumard, T. and Peyrot-Clausade, M. (1995) Bioerosion rates on coral reefs: interactions between macroborers, microborers and grazers (Moorea, French Polynesia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 113, 189-198.
- Chazottes, V., Le Campion-Alsumard, T., Peyrot-Clausade, M. and Cuet, P. (2002) The effects of eutrophication-related alterations to coral reef communities on agents and rates of bioerosion (Reunion Island, Indian Ocean). *Coral Reefs*, 21, 375–390.
- Chazottes, V., Reijmer, J.J.G. and Cordier, E. (2008) Sediment characteristics in reef areas influenced by eutrophication-related alterations of benthic communities and bioerosion processes. *Marine Geology*, 250, 114-127.
- Perry, C.T., Salter, M.A., Harborne, A.R., Crowley, S.F., Jelks, H.L. and Wilson, R.W. (2011) Fish as major carbonate mud producers and missing components of the tropical carbonate factory. *PNAS*, 108, 3865-3869.
- Perry, C.T., Lange, I.D. and Stuhr, M. (2023) Quantifying reef-derived sediment generation: Introducing the SedBudget methodology to support tropical coastline and island vulnerability studies. *Cambridge Prisms: Coastal Futures*, e26, 1–13.
- Salter, M.A., Perry, C.T. and Wilson, R.W. (2012) Production of mud-grade carbonates by marine fish: Crystalline products and their sedimentary significance. *Sedimentology*, 59, 2172- 2198.

We thank the reviewer for these suggestions. In the revised manuscript, we have added a reference to Chazottes et al. (2008): "*Moreover, anthropogenic eutrophication causes a change in the balance of coral versus coralline algae within the reefs (e.g., Chazottes et al., 2008), which further exacerbates the production of large amounts of mud-grade carbonate sediment by, in particular, biological erosion*" (Lines 159–162) and to Salter et al. (2012) (Lines 88 and 479).



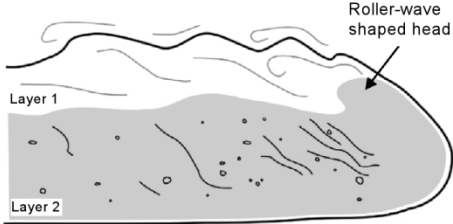
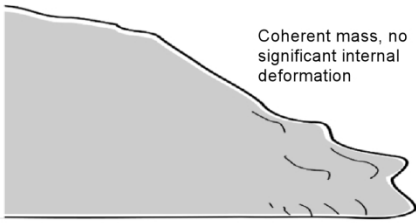
Flow type	Schematic drawing of flow type	CaCO ₃ concentrations in this study
Low-density turbidity current	 <p>No density interface, turbulence dominates</p>	1 – 45%
High-density turbidity current	 <p>Coherent fluid entrainment structures</p> <p>Layer 1</p> <p>Layer 2</p>	50 – 55%
Mud/debris flow	 <p>Roller-wave shaped head</p> <p>Layer 1</p> <p>Layer 2</p>	58%
Slide	 <p>Coherent mass, no significant internal deformation</p>	59%

TABLE 1 Sediment gravity flow type classification used in this study (modified after Baker & Baas, 2023).

186x190mm (300 x 300 DPI)

TABLE 2 Summary of experimental data of this study (mud-grade calcite) and Baker et al. (2017) (kaolinite, bentonite, silica flour)

Sediment type	Initial sediment concentration (%)	Run-out distance (m)	Maximum head velocity (m s^{-1})	Flow type
Mud-grade calcite	1	4.69 *	0.108	LDTC
Mud-grade calcite	5	4.69 *	0.239	LDTC
Mud-grade calcite	10	4.69 *	0.330	LDTC
Mud-grade calcite	15	4.69 *	0.404	LDTC
Mud-grade calcite	20	4.69 *	0.504	LDTC
Mud-grade calcite	25	4.69 *	0.572	LDTC
Mud-grade calcite	30	4.69 *	0.657	LDTC
Mud-grade calcite	35	4.69 *	0.696	LDTC
Mud-grade calcite	40	4.69 *	0.796	LDTC
Mud-grade calcite	45	4.69 *	0.851	LDTC
Mud-grade calcite	50	4.69 *	0.801	HDTC
Mud-grade calcite	53	3.75	0.781	HDTC
Mud-grade calcite	55	2.74	0.727	HDTC
Mud-grade calcite	58	1.16	0.551	Mud flow
Mud-grade calcite	59	0.75	0.445	Slide
Silica flour	1	4.69 *	0.11	LDTC
Silica flour	5	4.69 *	0.24	LDTC
Silica flour	10	4.69 *	0.34	LDTC
Silica flour	15	4.69 *	0.45	LDTC
Silica flour	25	4.69 *	0.58	LDTC
Silica flour	40	4.69 *	0.69	LDTC
Silica flour	44	4.69 *	0.71	LDTC
Silica flour	46	4.69 *	0.75	HDTC
Silica flour	47	4.66	0.75	HDTC
Silica flour	48	3.68	0.71	HDTC
Silica flour	49	2.82	0.71	HDTC
Silica flour	50	1.53	0.64	HDTC
Silica flour	51	0.96	0.61	Mud flow
Silica flour	52	0.49	0.29	Slide
Kaolinite clay	1	4.69 *	0.11	LDTC
Kaolinite clay	5	4.69 *	0.28	LDTC
Kaolinite clay	10	4.69 *	0.33	LDTC
Kaolinite clay	15	4.69 *	0.41	LDTC
Kaolinite clay	22	4.35	0.50	HDTC
Kaolinite clay	23	3.66	0.48	HDTC
Kaolinite clay	25	2.09	0.48	HDTC
Kaolinite clay	27	1.01	0.40	Mud flow
Kaolinite clay	29	0.45	0.29	Slide
Bentonite clay	1	4.69 *	0.1	LDTC
Bentonite clay	5	4.69 *	0.23	LDTC
Bentonite clay	10	4.69 *	0.31	LDTC
Bentonite clay	15	4.66	0.35	HDTC
Bentonite clay	16	3.77	0.37	HDTC
Bentonite clay	17	3.12	0.34	HDTC
Bentonite clay	18	1.42	0.27	Mud flow
Bentonite clay	19	1.22	0.22	Mud flow
Bentonite clay	20	0.22	0.07	Slide

LDTC = low-density turbidity current

HDTC = high-density turbidity current

* Minimum run-out distance

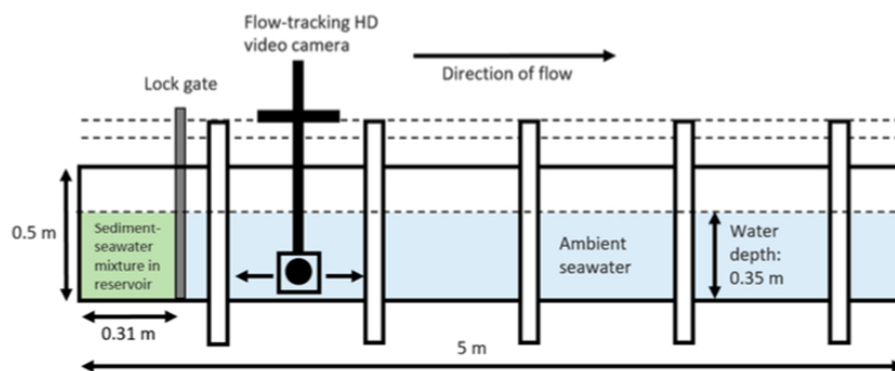


FIGURE 1 Experimental setup used for the lock-exchange tank experiments (after Baker et al. 2017)

162x70mm (144 x 144 DPI)

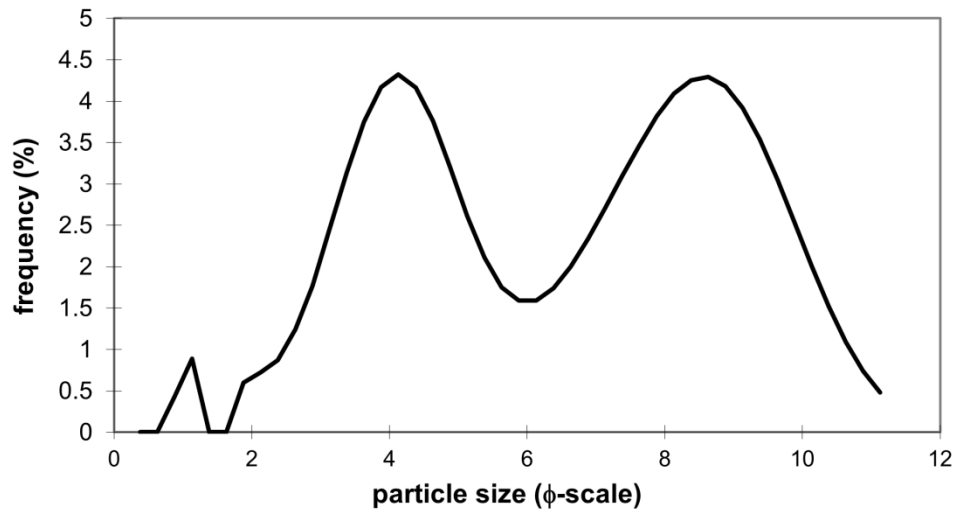


FIGURE 2 Frequency distribution curve of the particle size of the mud-grade calcite used in the experiments. Particle size is given in ϕ (phi)-values

157x85mm (330 x 330 DPI)

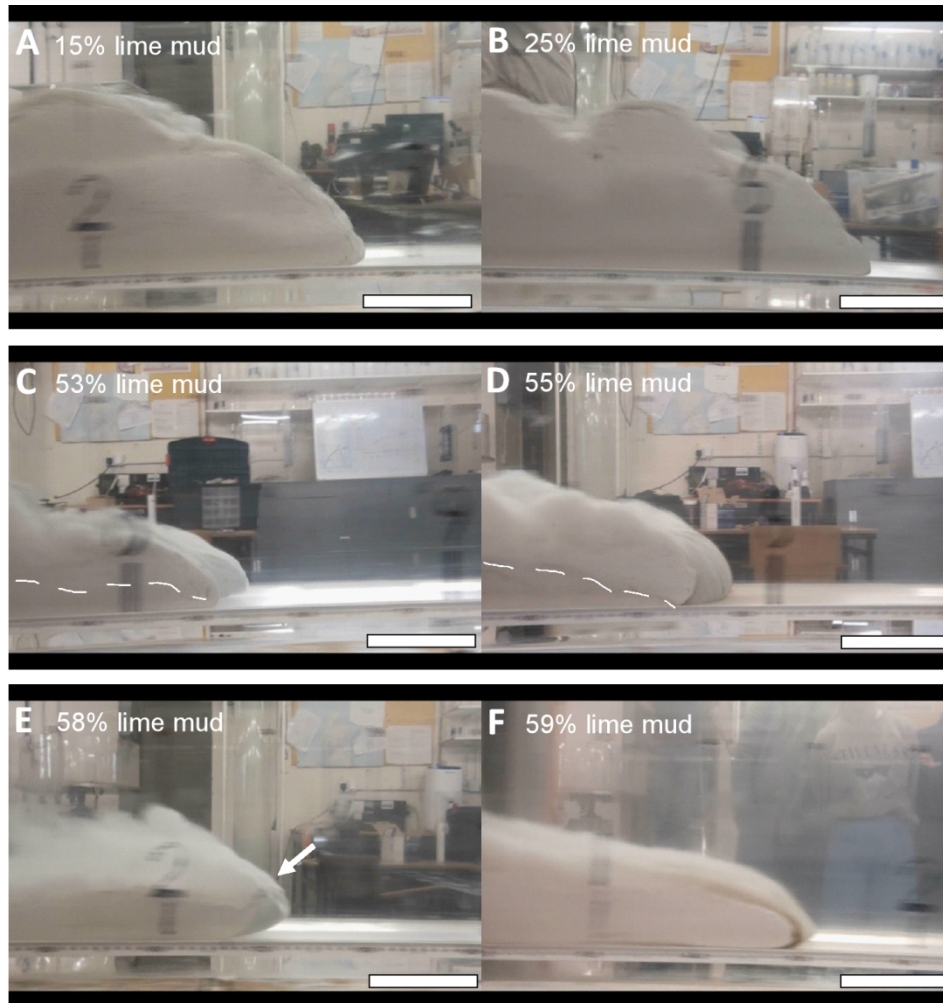


FIGURE 3 Video stills of the heads of selected CaCO_3 flows. (A) 15% low-density turbidity current, (B) 25% low-density turbidity current, (C) 53% high-density turbidity current, (D) 55% high-density turbidity current, (E) 58% mud flow, and (F) 59% slide. Dashed lines in (C) and (D) show density interfaces in high-density turbidity currents. Arrow in (E) points to lip region of mud flow. Scale bar is 100 mm long

133x140mm (300 x 300 DPI)

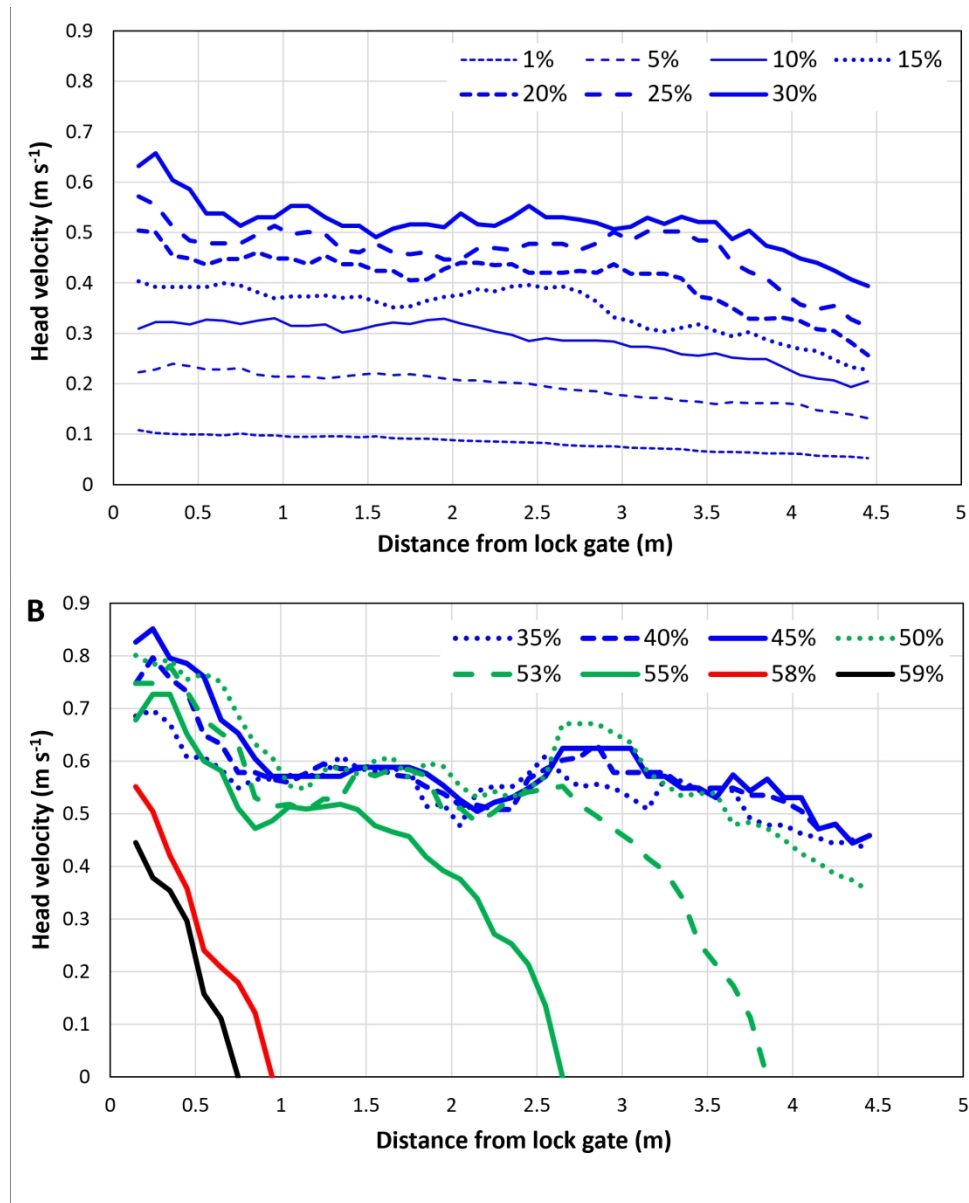


FIGURE 4 Head velocity against downflow distance from the lock gate for: (A) 1% to 30% mud-grade calcite flows; and (B) 35% to 59% mud-grade calcite flows. Low-density turbidity currents, high-density turbidity currents, mud flows, and slides are given in blue, green, red, and black, respectively

159x194mm (330 x 330 DPI)

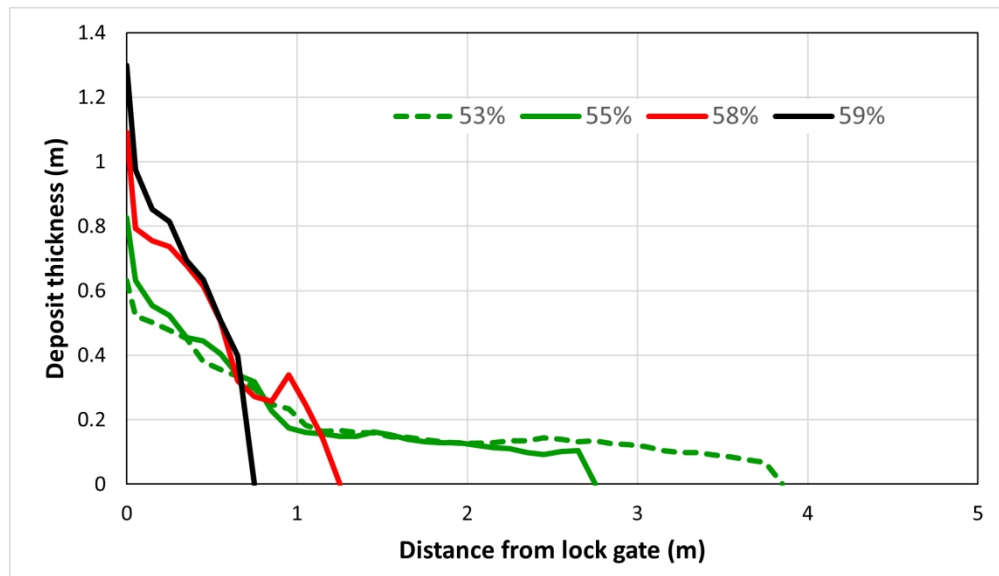


FIGURE 5 Deposit thickness trends of mud-grade calcite flows that had a measurable run-out distance. High-density turbidity currents, mud flow, and slide are given in green, red, and black, respectively

156x89mm (330 x 330 DPI)

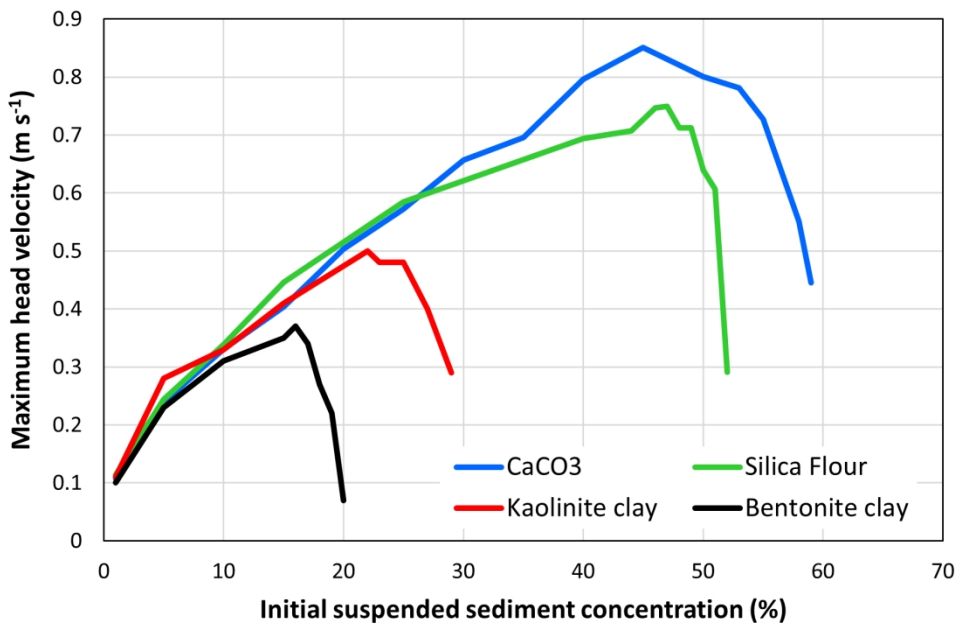


FIGURE 6 Maximum head velocity of CaCO₃, kaolinite, bentonite, and silica flour flows against initial suspended sediment concentration

150x99mm (330 x 330 DPI)

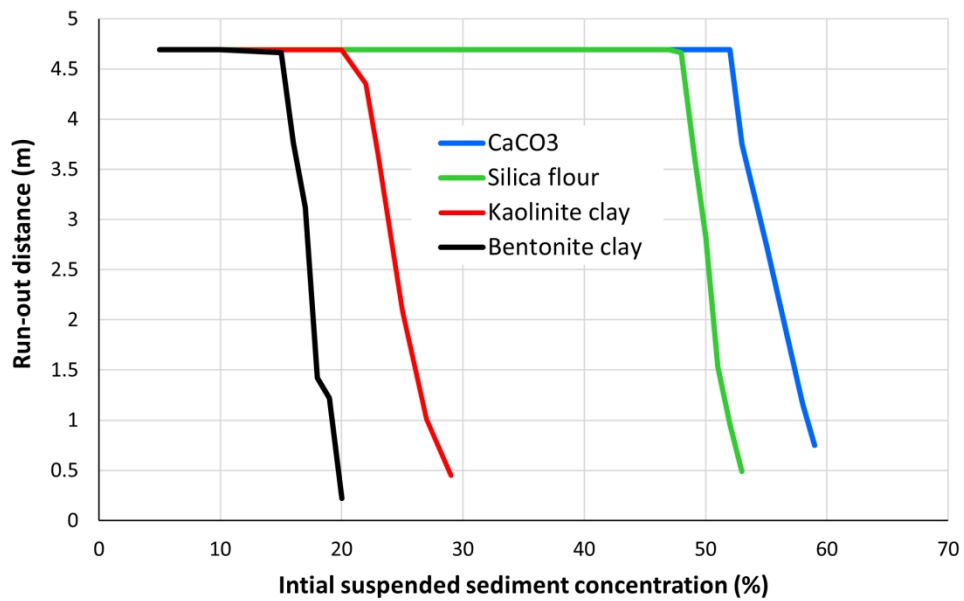


FIGURE 7 Run-out distance of CaCO₃, kaolinite, bentonite, and silica flour flows against initial suspended sediment concentration. Run-out distances of 4.69 m denote minimum values; these flows reflected off the end of the tank

159x104mm (330 x 330 DPI)

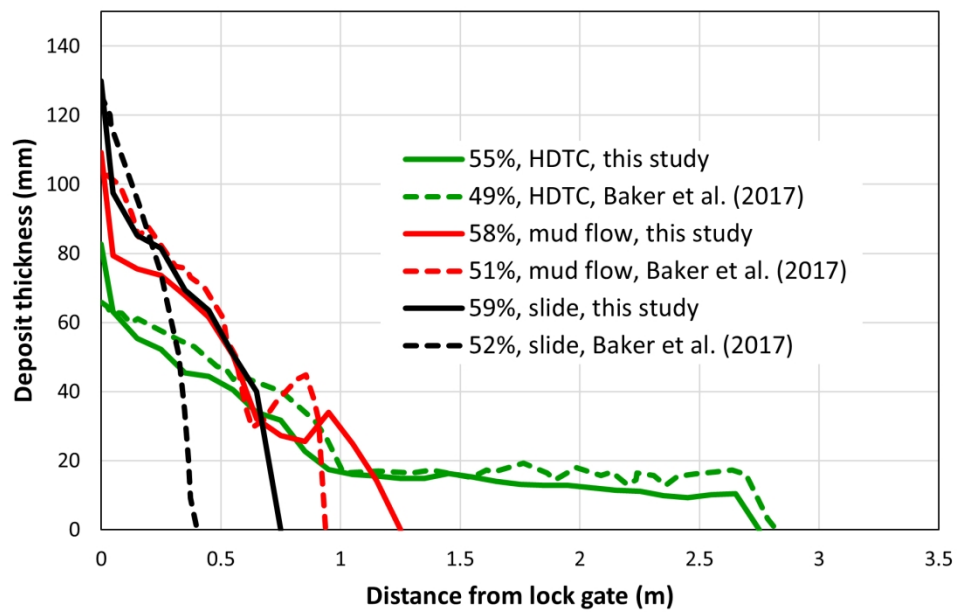


FIGURE 8 Deposit thickness trends of mud-grade calcite and silica-flour flows against downflow distance from the lock gate, comparing selected high-density turbidity currents (HDTCs), mud flows, and slides from this study and Baker et al. (2017)

156x99mm (330 x 330 DPI)