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1 **Entangled external and internal controls on submarine fan evolution:** 2 **an experimental perspective**

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9 **Abstract**

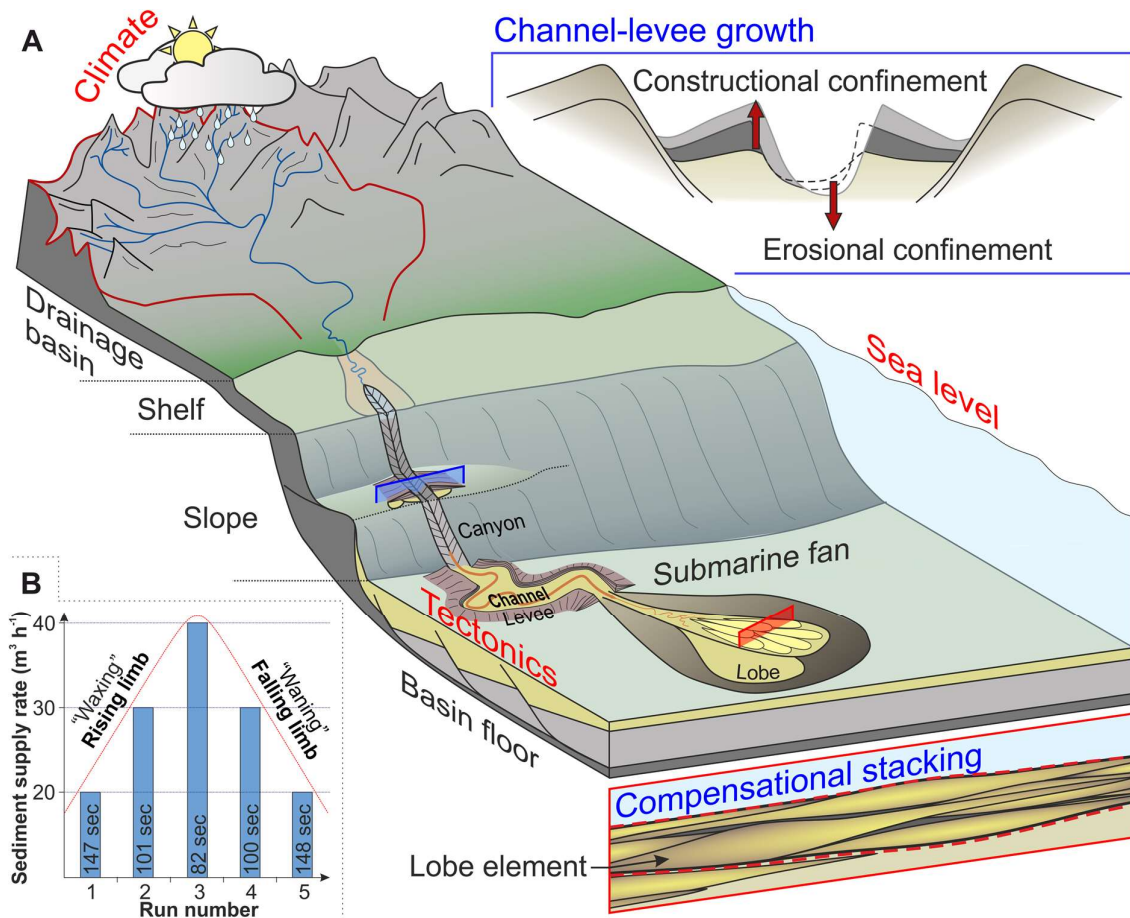
10 Submarine fans are formed by sediment-laden flows shed from continental margins into ocean basins.
11 Their morphology represents the interplay of external controls such as tectonics, climate, and sea-
12 level with internal processes including channel migration and lobe compensation. However, the
13 nature of this interaction is poorly understood. We used physical modelling to represent the evolution
14 of a natural-scale submarine fan deposited during an externally forced waxing-to-waning sediment
15 supply cycle. This was achieved by running five successive experimental turbidity currents with
16 incrementally increasing then decreasing sediment supply rates. Deposits built upon the deposits of
17 earlier flows and the distribution of erosion and deposition after each flow was recorded using digital
18 elevation models. Initially, increasing sediment supply rate (waxing phase) led to widening and
19 deepening of the slope channel, with basin-floor deposits compensationally stepping forwards into
20 the basin, favouring topographic lows. When sediment supply rate was decreased (waning phase), the
21 slope-channel filled as the bulk of the deposit abruptly back-stepped due to interaction with
22 depositional topography. Therefore, despite flows in the waxing and waning phases of sediment
23 supply having nominally identical input conditions (i.e. sediment concentration, supply rate, grain size
24 etc.), depositional relief led to development of markedly different deposits. This demonstrates how
25 external controls can be preserved in the depositional record through progradation of the basin floor
26 deposits but that internal processes such as compensational stacking progressively obscure this signal
27 through time. This evolution serves as an additional potential mechanism to explain commonly
28 observed coarsening- and thickening-upwards lobe deposits, with abrupt transition to thin fine-
29 grained deposits. Meanwhile within the slope channel, external forcing was more readily detectable
30 through time, with less internally driven reorganisation. This validates many existing conceptual
31 models and outcrop observations that channels are more influenced by external forcing whilst internal
32 processes dominate basin floor lobe deposits in submarine fans.

33 **KEYWORDS**

34 Sediment gravity flow, allogenic, autogenic, submarine fan architecture, experimental modelling

35 **1 INTRODUCTION**

36 Submarine fans, the terminal portion of sedimentary source-to-sink systems, are amongst the largest
 37 sedimentary accumulations on the planet (Normark, 1970; Posamentier and Kolla, 2003; Talling et al.,
 38 2007). Shaped by sediment gravity flows which deliver a range of natural and (more recently)
 39 anthropogenic materials to deep-water environments, they provide an invaluable record of Earth's
 40 climatic and tectonic history, and the dispersal of sediment, organic carbon and pollutants in the deep
 41 ocean (Emmel and Curray, 1983; Pirmez and Imran, 2003; Deptuck et al., 2008; Gwiazda et al., 2015;
 42 Picot et al., 2016, 2019; Rabouille et al., 2019). Both external and internal processes control the
 43 morphodynamic evolution and stratigraphic record of submarine fans (Figure 1; Beerbower, 1964;
 44 Cecil 2003). External controls refer to those outside the sedimentary system, including sea-level,
 45 climate, and tectonics (Normark et al., 2006; Knudson and Hendy, 2009). These factors are responsible
 46 for large-scale variations in the rate, volume, and routing of sediment supply to deep-marine systems,
 47 and for the total available accommodation space (Maslin et al., 2006; Nelson et al., 2009). Internal
 48 controls are self-organisation processes, driven by deposition and erosion. They include channel
 49 avulsion, levee growth and compensational stacking (i.e. preferential deposition in topographic lows)
 50 of lobes and their constituent building blocks; 'lobe elements' (Figure 1; Pr elat et al., 2009; Wang et
 51 al. 2011). Understanding these external and internal controls can aid interpretation of Earth's
 52 geological and climatic record.



53
 54 **FIGURE 1** Conceptual model of a source-to-sink sedimentary system. (A) External and internal controls (red and blue text
 55 respectively) on typical submarine fans. Cross-section locations are indicated on the model. The typical sub-environments of
 56 a main channel, levees, and lobes are labeled. Compensational stacking image modified from Pr elat et al. (2009) and source-
 57 to-sink cartoon modified from S omme et al. (2009). (b) Variation in sediment supply rate (suspension discharge) between

58 experimental runs. This increase followed by a decrease of sediment supply rate was used to emulate an externally forced
59 waxing-to-waning sediment supply cycle in this study. The duration of each run is indicated on each bar.

60 Many investigations have been made into the relative control of external and internal forces in fluvio-
61 deltaic environments (e.g. Yang et al., 1998; Karamitopoulos 2014; Mikeš et al., 2015, Toby et al.,
62 2019); fewer studies have considered the relative influence of external and internal controls on deep-
63 water sedimentary systems. Source-to-sink analyses have been conducted that variably consider
64 sediment budgeting, routing, and provenance to demonstrate the efficiency of sediment delivery to
65 deep water settings (e.g. Romans et al., 2009; Sømme et al. 2009; Covault et al., 2010; Covault et al.,
66 2011; Blum et al., 2018). Other studies have investigated the effect of sediment supply and how this
67 directly impacts the architectural evolution of modern submarine channels and lobes (Dorrell et al.,
68 2015; Jobe et al., 2015; 2017). Burgess et al. (2019) used power-spectrum analysis to identify a ‘signal
69 bump’ (an increase in the number of spectral peaks at a given frequency) to indicate preserved
70 external signals in stratigraphy. However, the presence of internal fan organisation can make this
71 signal bump difficult to detect (Burgess et al. 2019). This is supported by research that suggests bulk
72 external signals can be modulated or entirely ‘shredded’ by internal processes (Jerolmack and Paola,
73 2010; Wang et al., 2011; Romans et al., 2016; Harris et al., 2018). In some cases, however, internal
74 processes may amplify external signals creating positive feedback loops, such as increasing channel
75 incision on a slope due to flow confinement within the channel (Hodgson et al., 2016; de Leeuw et al.,
76 2018a). Recent work has shown that external forcing can affect the recurrence of large-volume
77 canyon-flushing turbidity currents, either through sea-level variability (Allin et al. 2018), or
78 tectonically-influenced canyon position with respect to its sediment supply system (Jobe et al., 2011).
79 This, and work by Bernhardt et al. (2015) on the combined importance of tectonic setting, climate,
80 and earthquakes along continental margins further supports the view that external signals can be
81 expressed in deep-marine environments. As such, to determine the fidelity of fans for tectonic or
82 paleoclimatic reconstruction, it is essential to understand if and how signals are preserved. If external
83 signals are only partially preserved, it will be necessary to acquire more robust datasets (e.g. multiple
84 core locations) in natural systems in order to confidently reconstruct turbidity current volume and
85 recurrence across sediment routing systems (Jobe et al., 2018).

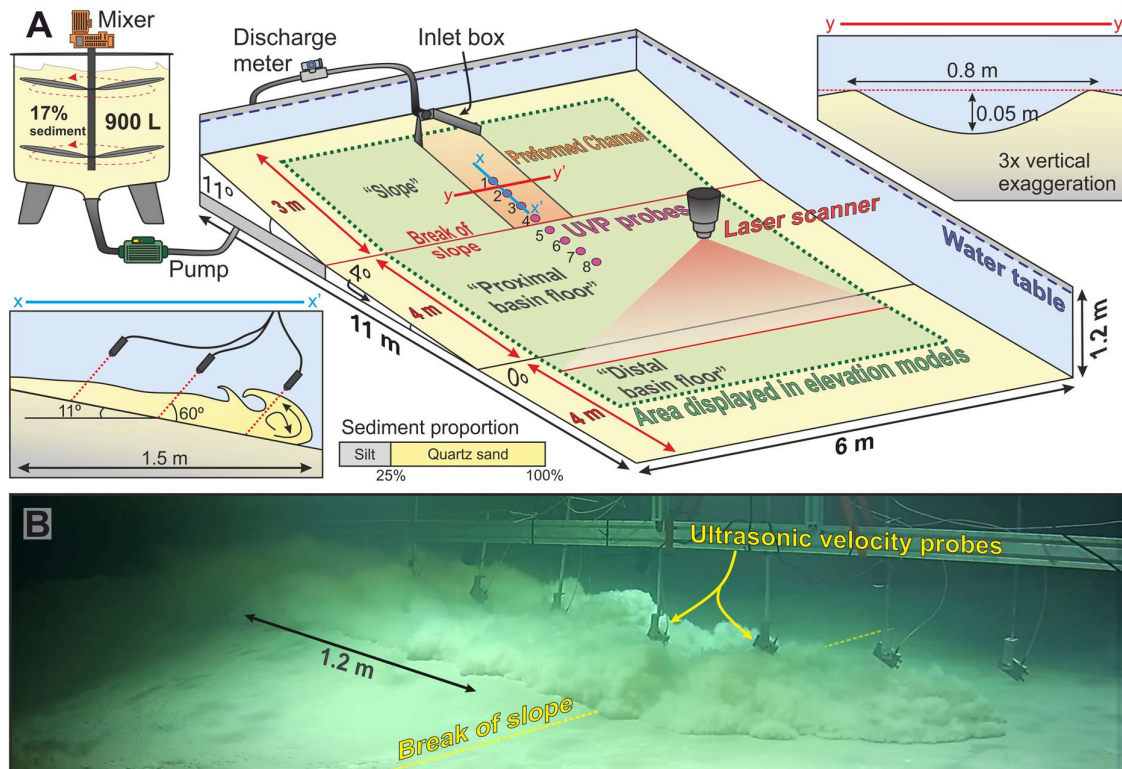
86 Here, we ask the question: how is an externally forced sediment supply cycle recorded in the
87 morphology and stratigraphy of a submarine fan? We investigate this question using a series of
88 experimental turbidity currents with incrementally increasing then decreasing sediment supply rates
89 (suspension discharge from a mixing tank) (Figure 1B). Building upon similar experimental studies on
90 submarine channels and lobes (e.g. Mohrig and Buttles, 2007; Kane et al., 2008; Cantelli et al., 2011;
91 Janocko et al., 2013; Fernandez et al., 2014), we examine the morphodynamics of this system, and
92 how the preserved stratigraphic record relates to the external signal. The results are compared
93 explicitly to the exhumed Permian deposits of ‘Fan 3’, in the Karoo Basin, South Africa (Prélat et al.,
94 2009; Groenenberg et al., 2010; Kane et al., 2017) - where high stratigraphic resolution allows for
95 reasonable comparisons to be made - as an illustration of their applicability in the interpretation of
96 natural submarine fan deposits.

97 **2 METHODS**

98 **2.1 Set-up**

99 The experiments were conducted at Utrecht University in the Eurotank Flume Laboratory (Figure 2).
100 The experimental basin was 11 x 6 m in planform and filled to a water level of 1.2 m above the
101 horizontal floor. The initial tank bathymetry consisted of an 11° slope of 3 m in length (the “slope”),

102 followed by a 4° slope of 4 m in length (the “proximal basin floor”), ending in a 4 m long horizontal
 103 “distal basin floor”. This slope gradient, high for natural settings, promoted flow velocities high enough
 104 to erode sediment and bypass sediment to the basin floor (de Leeuw et al. 2016). The tank floor was
 105 covered by approximately 20 cm of loose sand of the same grain-size distribution as the turbidity
 106 current mixture (Figure 3F) enabling turbidity currents to erode into the substrate. A straight, 0.8 m
 107 wide, 0.05 m deep, symmetrical channel form was sculpted into the initial 11° slope from the inlet box
 108 to the break of slope (Figure 2A). The dimensions of this initial channel form were selected based on
 109 the dimensions of a self-formed channel produced by de Leeuw et al. (2016). The turbidity currents
 110 entered the basin via an inlet box with an un-erodible base of 0.7 m in length and gradually expanding
 111 sides before continuing down the sediment covered slope. All boundary conditions were consistent
 112 across all runs except for suspension discharge (see section 2.3 for details; Table 1; Figure 3).



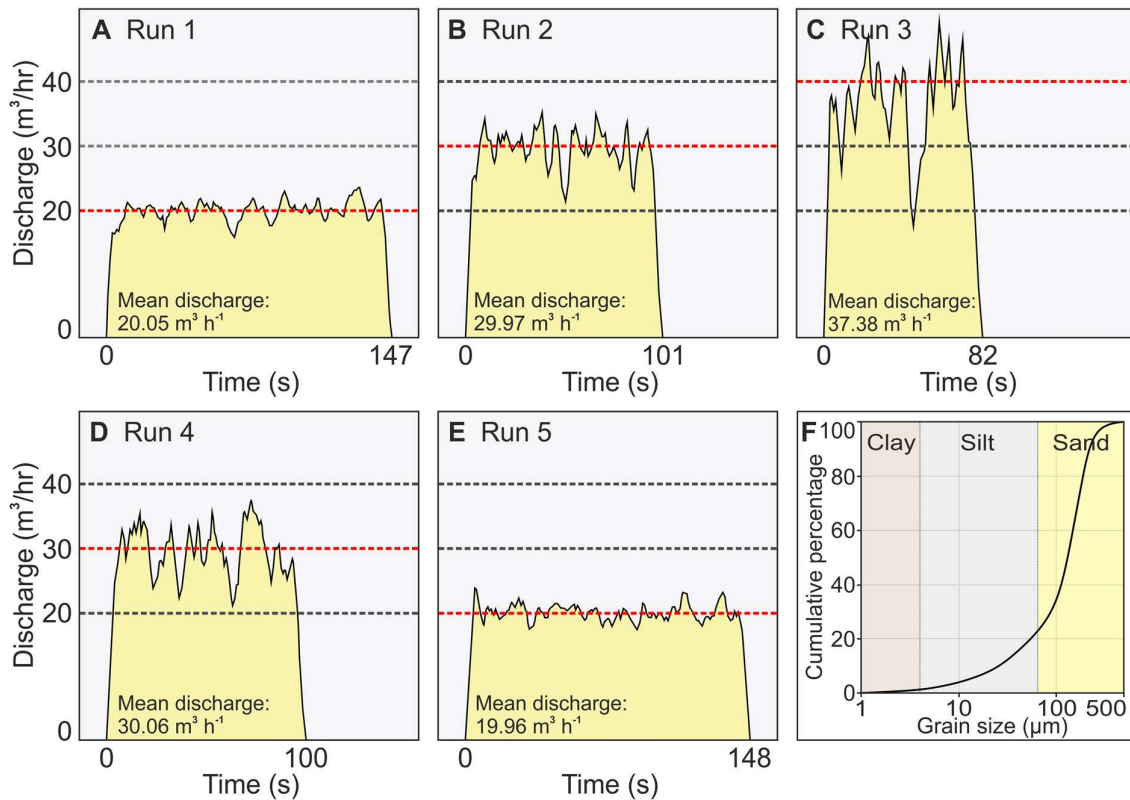
113
 114 **FIGURE 2** 3D flume tank set-up at the Eurotank Flume Laboratory. (A) Schematic diagram of the flume tank including key
 115 geometries and data collection methods. The sediment-water mixtures were homogenised in a mixing tank before being
 116 pumped into the flume tank via the inlet box at the top of the slope. The turbidity currents flowed down a preformed channel
 117 on the slope before becoming unconfined at the proximal basin floor. Suspension discharge rates were measured using a
 118 discharge meter attached to the supply pipe. Flow velocities were recorded using eight ultrasonic velocity probes (UVPs)
 119 positioned along the axis of the channel and across the break of slope at 40 cm intervals. Digital elevation models (DEMs)
 120 were generated using a precision laser scanner. The basin was divided into three separate sections based on slope profile:
 121 Slope, proximal basin floor, and distal basin floor. (B) Image of Run 1 immediately after the head of the flow passed the break
 122 of slope. The flow steadily expanded upon reaching the proximal basin floor due to exiting of the confinement.

123 2.2 Turbidity current suspension parameters

124 Prior to each experiment, the sediment mixture was prepared in a separate mixing tank with two
125 impellers that homogenised the mixture (Figure 2). The volume of the suspension (sediment and water
126 mixture) was 900 litres (L) in each event; sediment contributed 17% of this. Quartz sand (*Sibelco BR-*
127 *37*) with a specific density of 2650 kg m^{-3} constituted 75% (300 kg) of the total sediment suspension
128 volume with the remaining fraction being 100 kg of silt-sized ground glass. The median grain size (D_{50})
129 of the mixture was $131 \mu\text{m}$, with a D_{10} of $25 \mu\text{m}$ and a D_{90} of $223 \mu\text{m}$ (Figure 3F). Grain size was analysed
130 using a Malvern Mastersizer particle sizer (Malvern Instruments Limited, Malvern, UK).

131 2.3 Experimental procedure

132 Five successive sediment-laden turbidity currents entered the basin from the inlet at the top of the
133 slope (Figure 2). These currents were created by pumping the suspension from the mixing tank to the
134 basin via a supply pipe. Suspension discharge (i.e. volume per hour of flow into the tank) was
135 monitored using a discharge meter (Khrohne Optiflux 2300) mounted on the supply pipe and
136 regulated using a Labview control system (National Instruments Corporation (UK) Limited, Newbury,
137 UK). To simulate an external control on the system, in this case a waxing-to-waning sediment supply
138 cycle, the suspension discharge rate was increased between runs 1 to 3 from $20 \text{ m}^3 \text{ h}^{-1}$, to $30 \text{ m}^3 \text{ h}^{-1}$,
139 then $40 \text{ m}^3 \text{ h}^{-1}$, before being decreased back to $30 \text{ m}^3 \text{ h}^{-1}$, and then $20 \text{ m}^3 \text{ h}^{-1}$ in runs 4 and 5 respectively
140 (Figure 1B and Figure 3). Discharge rate fluctuated around the reference value in each run, however,
141 this variability averaged out over the course of each run and does not appear to have had a tangible
142 impact on the resultant flows/deposits (Figure 3). Minimum and maximum sediment suspension
143 discharge rates (i.e. boundary conditions) were identified by running a separate series of pilot
144 experiments. A suspension discharge rate of $10 \text{ m}^3 \text{ h}^{-1}$ resulted in immediate deposition of the
145 sediment load upon entering the basin whilst $50 \text{ m}^3 \text{ h}^{-1}$ resulted in excessive erosion and sediment
146 transport beyond the range of practicable measurement (Supporting Figures 2 and 3). Consequently,
147 a minimum suspension discharge rate of $20 \text{ m}^3 \text{ h}^{-1}$, and maximum of $40 \text{ m}^3 \text{ h}^{-1}$ was used for the main
148 experiment, with $30 \text{ m}^3 \text{ h}^{-1}$ used to represent the intermediate phase of the rising and falling limbs
149 (Figures 3). Runs 1 to 5 ran for 147, 101, 82, 100, 148 seconds respectively (Figure 3), each time
150 draining the 900 litre mixing tank. Even though each run was technically an individual ‘flow event’,
151 they are considered to each represent protracted phases of sediment delivery to the system. In each
152 phase, a similar volume of sediment was supplied, the effect of the higher discharge being that
153 turbidity currents were larger, and more powerful. Our scenario should thus be seen as an analogue
154 for increasing then decreasing turbidity current strength during an externally forced cycle (e.g. sea-
155 level, climate, or tectonic variability). With this specification in mind, the suspension discharge rate
156 shall henceforth be referred to as ‘sediment supply rate’ for simplicity. A base case equivalent where
157 sediment supply rate was kept constant was not included in this study as earlier works serve to fill this
158 role and are referred to where appropriate (e.g. Fernandez et al., 2014; de Leeuw et al., 2018a, 2018b;
159 Spychala et al., 2019).



160

161 **FIGURE 3** Suspension discharge (i.e. sediment supply rate) over time for each run (A-E) and cumulative grain size
 162 distribution. (A-E) Reference discharge values are given by dashed red lines. When measured sediment supply rate deviated
 163 from the reference value (e.g. 20, 30, 40 m³ h⁻¹), the pump speed was manually adjusted to compensate. Discharge readings
 164 became progressively more difficult to stabilise with increasing discharge rates, resulting in some discharge variability in runs
 165 2, 3, and 4. The mean discharge was calculated using the duration of the whole run minus the first and last 15 seconds. (F)
 166 Cumulative grain size distribution for the suspended sediment in each flow/run and for the erodible substrate of the tank.

167 Eight Ultrasonic Velocity Profiler (UVP) probes (MET-FLOW, UVP-DUO-MAX, 1 MHz) were positioned
 168 15 cm above the substrate to record the flow field during the experiments. The probes had a spatial
 169 resolution of 0.64 mm and a measurement frequency of 1.81 Hz. Their beams were oriented at an
 170 angle of 60° relative to the local bed, facing incoming flows along the slope channel axis and across
 171 the break of slope at 40 cm intervals (Figure 2). The UVP probes measured the velocity of sediment
 172 grains along a vector aligned with the probe axis. Bed-parallel velocity was calculated from the
 173 measured data using trigonometry under the assumption that bed-normal velocity was zero. This was
 174 plotted against time for each run and used to infer bed-base deposition and erosion through time as
 175 the bed base increased or decreased in height (Supporting Figures 4-8). Time-averaging the velocity
 176 data created profiles that enabled analysis of the downslope velocity evolution (Figure 5). These
 177 profiles were compared between runs to examine how velocities changed as the experiment
 178 progressed. Velocity averages were taken for the entire run durations, minus the head and tail of each
 179 flow (first and last five seconds).

180 Run deposits accumulated sequentially, illustrating how the turbidity currents responded to the
 181 evolving topography in the basin. After each experimental run, the basin was drained, and the deposit
 182 was scanned using a high-resolution laser scanner. This allowed production of digital elevation models
 183 (DEMs) with a horizontal grid spacing of 2 x 2 mm, and a vertical resolution of < 0.5 mm. By comparing
 184 DEMs from before and after each experimental run, deposition/erosion maps were generated (Figure
 185 4 and Supporting Figure 1). Due to high amounts of erosion directly after the inlet box where flows

186 passed over the boundary from un-erodible to erodible substrate, the upper 1 m of the slope channel
187 was restored to its original 0.8 x 0.05 m geometry to maintain the incoming flow properties between
188 experimental runs.

189 2.4 Flow Scaling

190 To realistically represent a natural system that can erode and transport sediment in suspension
191 downslope, the experimental turbidity currents of this study utilised Shields scaling (Shields, 1936).
192 This approach follows de Leeuw et al. (2016) and Pohl et al. (2019), using the Shields parameter (τ^*),
193 which is the ratio between bed shear stress and gravitational forces acting on the sediment, and the
194 particle Reynolds number (Re_p), which controls the hydrodynamic condition at the base of the flow
195 (Supporting Figure 9). A Shields parameter comparable to natural systems has been achieved in our
196 experiments by using a high sediment concentration (17% of total volume) and a steep (11°) slope
197 (Supporting Figure 9, Supporting Table 1; Xu et al., 2014; Azpiroz-Zabala, et al., 2017). The particle
198 Reynolds number is subcategorised as ‘hydraulically smooth’ ($Re_p < 5$), ‘transitionally rough’ (Re_p
199 between 5 and 70), or ‘hydraulically rough’ ($Re_p > 70$). Measurements from natural turbidity currents
200 document a transitionally rough regime whilst this experiment plots within the transitionally rough
201 regime in the slope channel, and spans the transitionally rough to hydraulically smooth regimes on
202 the basin floor (Supporting Figure 9, Supporting Table 1; Xu et al., 2014; Azpiroz-Zabala, et al., 2017).
203 The fine-grained sand used for the flow and substrate ($D_{50} = 131$) ensures transitionally rough flow in
204 the slope channel, promoting erosion through turbulent interaction with the bed.

205 The Shields parameter and the particle Reynolds number are calculated with:

$$206 \quad \tau^* = \frac{U^{*2}}{(\rho_s/\rho_f - 1)gD_{50}} \quad (1)$$

$$207 \quad Re_p = \frac{U^*D_{50}}{\nu} \quad (2)$$

208 where ρ_s is the sediment density (2650 kg / m³), ρ_f is the current density, g is the gravitational
209 acceleration (9.81 m s⁻¹), D_{50} is the median grain size (131 μm), ν is the kinematic viscosity of fresh
210 water at 20°C (1x10⁻⁶), and U^* is the shear velocity, estimated using (Middleton and Southard, 1984;
211 van Rijn, 1993):

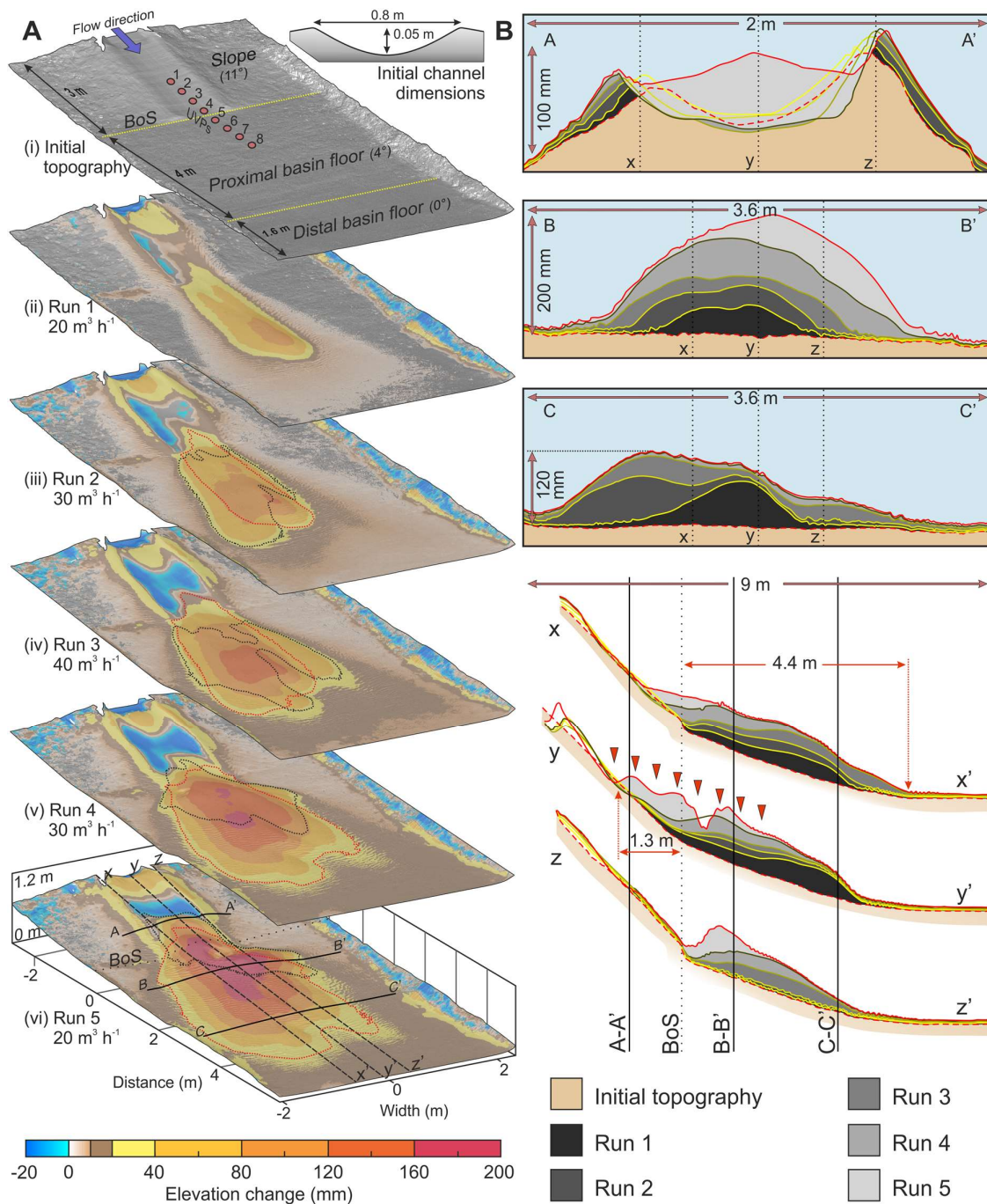
$$212 \quad U^* = U_{max}k \left[\ln \left(h_{max}/0.1D_{90} \right) \right]^{-1} \quad (5)$$

213 where U_{max} is the time-averaged velocity maximum, h_{max} is the height of the velocity maximum, k is
214 the von Kármán’s constant (0.40), and the D_{90} of the grain size was 223 μm. See Supporting Table 1
215 for breakdown of dynamic and sedimentary experimental flow properties.

216 With this scaling approach we ensure the mobility of particles in the flow, generating turbidity currents
217 that can erode, suspend, or deposit sediment. The depositional pattern formed by these flows allows
218 identification of the general response of the system to external and internal controls. Section 4.2
219 places the experimental deposits into a hierarchical framework to assist comparison with natural
220 settings. However, it should be noted that the purpose of these experiments is not to directly replicate
221 the exact depositional architecture and hierarchy of natural settings, but to provide a practical
222 reference for their development.

223 **3 RESULTS**

224 **3.1 Fan evolution**



225

226 **FIGURE 4** Maps of cumulative deposition and erosion and associated cross-sections. (A) Digital Elevation Models (DEMs)
 227 of cumulative deposition (warm colours) and erosion (blue colours) from runs 1 – 5. The dotted red line on each DEM shows
 228 the area of the cumulative deposition from the previous runs that is > 20 mm thick. The dotted black line shows the area of
 229 the deposit from each respective individual run (> 20 mm thick). Locations are indicated on run 5 in (A) and intersections are indicated on each cross-section. Red lines
 230 denote the final (solid line) and initial (dashed line) topography. Interfaces between runs in each cross-section are
 231 gradationally darker yellow, from first to last respectively, to aid differentiation of discrete runs. Red arrowheads on cross-
 232 section y-y' indicate UVP probe locations. BoS = break of slope.
 233

234 The five turbidity currents released into the basin travelled down the slope channel and continued to
235 the unconfined basin floor, creating an evolving pattern of erosion and deposition. The ‘submarine
236 fan’ of this experimental study consists of all areas of the slope and basin floor where erosion and
237 deposition took place and is considered equivalent to both the channel-levee and lobe environments
238 of natural-scale systems (Figure 1). Figure 4 visually documents the morphological evolution of the
239 system using composite erosion/deposition maps and associated cross-sections through the
240 stratigraphy (for individual run erosion/deposition maps see Supporting Figure 1). The composite
241 deposit grew with each event, whilst the amount of channel incision and levee deposition varied from
242 run to run (Figure 4 and Supporting Figure 1). The results from each run are detailed as follows:

243 (i) The initial topography consisted of a preformed 0.8 m x 0.05 m channel that extended down the
244 11° slope before terminating upon the flat, gently dipping (4° then 0°) basin floor.

245 (ii) Experimental run 1 ($20 \text{ m}^3 \text{ h}^{-1}$) transferred most of its sediment load to the basin floor, however
246 some deposition occurred along the length of the channel (Figure 4). An elongate area was eroded on
247 the right side of the channel axis (looking downstream), widening and deepening the channel.
248 Overbank deposition took place on the flanks of the slope-channel where the flow spilled outside its
249 confinement. Maximum overbank deposition took place directly adjacent to the channel and thinned
250 rapidly away from the channel margins. Upon exiting the channel confinement at the break of slope,
251 the flow deposited its load centrally on the proximal basin floor in a broadly elongate and lobate
252 shape. The maximum deposit thickness was 107 mm, approximately 2.5 m from the break of slope. A
253 thin (< 10 mm) fringe of sediment extended out beyond the main body of the deposit and onto the
254 distal basin floor.

255 (iii) During run 2 ($30 \text{ m}^3 \text{ h}^{-1}$), erosion increased across the slope channel, dominantly towards the right
256 of the channel axis. An increase in overbank deposition was observed, leading to enhanced flow
257 confinement on the slope by both erosional and constructional means. This overbank deposition built
258 upon the deposition from run 1, resulting in wedge-shaped geometries that thinned away from the
259 channel margins; they were consequently classified as levees (Kane et al., 2007; de Leeuw et al.,
260 2018a). On the basin floor, depositional topography created by run 1 deflected the bulk of the flow to
261 the right, causing a lateral shift of maximum deposition (69 mm thick) to the right and compensational
262 stacking of the deposit. A small portion of the flow also deflected to the left of the run 1 deposit,
263 resulting in a thin (~10 mm) deposit. Overall, the deposit from run 2 extended 12% farther into the
264 basin than the previous deposit (from 3.4 m to 3.8 m from the break of slope).

265 (iv) Run 3 ($40 \text{ m}^3 \text{ h}^{-1}$) represented the peak of the sediment supply curve. Even greater amounts of
266 erosion were observed in the channel axis and substantial overbank deposition occurred. The deposit
267 extended 8% farther into the basin than the deposit of run 2 (to 4.1 m from the break of slope).
268 Compensational stacking continued, with deposition being spread approximately evenly on either side
269 of the initial deposit looking down-flow. Maximum deposit thickness was 53 mm and was found to the
270 left of the basin with respect to flow direction. Notably, this maximum thickness was approximately
271 half that of the deposit of run 1, with sediment being distributed more evenly across the basin floor
272 (see Supporting Figure 1 for clarity).

273 (v) Run 4 ($30 \text{ m}^3 \text{ h}^{-1}$) marked the beginning of waning sediment supply. There was a decrease in channel
274 erosion and limited overbank deposition associated with this reduction in sediment supply rate. On
275 the basin floor, the deposit back-stepped considerably from the position of the run 3 deposit,

276 extending 34% less into the basin than the deposit of run 3 (to 2.7 m from the break of slope). The
277 run 4 deposit exhibited less compensation, stacking more aggradationally (maximum thickness 65
278 mm) having back-stepped to onlap the slope and begin infilling the slope channel.

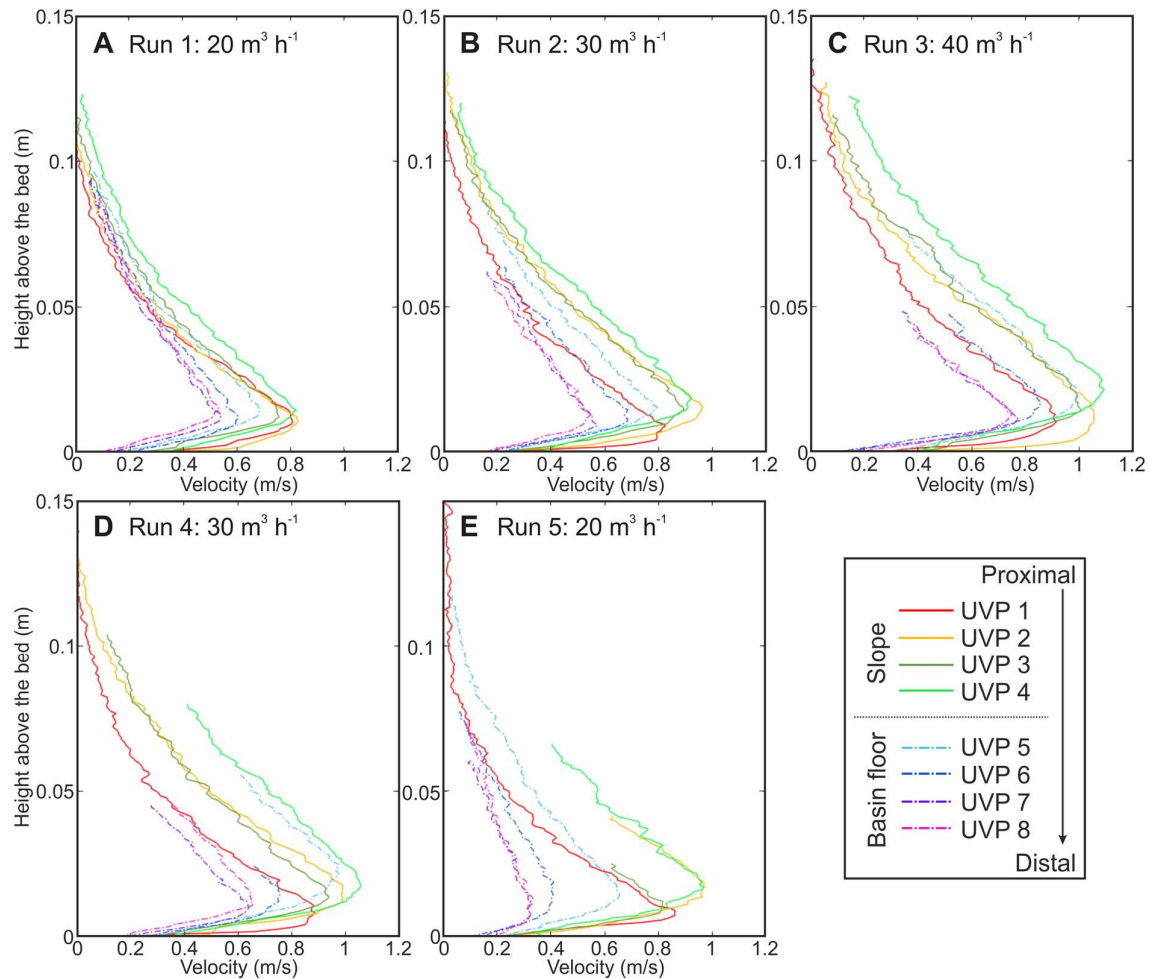
279 (vi) Run 5 ($20 \text{ m}^3 \text{ h}^{-1}$) saw a continuation of the back-stepping trend observed in run 4, extending 41%
280 less into the basin than the deposit of run 4 (1.6 m from the break of slope), with more channel
281 deposition and effectively no overbank deposition. The maximum deposit thickness was 104 mm,
282 located approximately at the position of the original break of slope (Figure 4A). A small area ($\sim 345 \times$
283 445 mm) of erosion developed in the middle of the deposit contemporaneously with the flow event
284 (Figure 4; Supporting Figure 1). This syn-depositional event is evidenced by a lowering of the bed-base
285 recorded in velocity/time plots produced using ultrasonic velocity profile (UVP) probe data, indicating
286 this event took place during the flow event (Supporting Figure 8).

287 *Summary.* When sediment supply rate increased, erosion within the channel increased and overbank
288 deposition continued, resulting in a progressive widening and deepening of the channel (Figure 4B,
289 cross-section A-A'). Across the same interval, each successive flow deposit extended farther into the
290 basin than the previous. During this time deposits stacked compensationally (Figure 4). A reversal of
291 the erosional-depositional trend was observed when the sediment supply rate was reduced. Erosion
292 in the channel axis and overbank deposition declined, and the basal deposit abruptly back-stepped
293 up the slope to fill the channel. The fringe deposits continued to aggrade steadily on the distal basin
294 floor despite forward-stepping, back-stepping, and compensation exhibited by the main deposit
295 (Figures 4 and 9).

296 3.2 Flow-field evolution

297 Ultrasonic velocity profile (UVP) probes were placed along the axis of the channel and across the break
298 of slope to record the downslope evolution of the flow field (Figures 2 and 5). Velocities were relatively
299 higher on the slope ($0.76\text{-}1.09 \text{ m s}^{-1}$) (UVPs 1-4), before progressive deceleration took place beyond
300 the break of slope on the basin floor ($0.32\text{-}0.99 \text{ m s}^{-1}$) (Figure 5, UVPs 5-8). This spatial change in
301 velocity was likely driven by the steeper gradient and flow confinement on the slope, versus the
302 gentler unconfined setting of the basin floor. Based on the distribution of erosion and deposition
303 across the experimental basin, it can be inferred that higher velocities on the slope promoted erosion
304 and sediment bypass whilst lower velocities on the basin floor led to deposition.

305 The spatial evolution of the flow field for runs 1 to 5 is presented in time-averaged velocity profiles to
306 show how flows developed between runs (Figure 5). The maximum velocity (U_{max}) on the slope
307 increased from approximately 0.83 m s^{-1} (UVP 2) in run 1, to 1.09 m s^{-1} in run 3 (UVP 1) as sediment
308 supply rate was increased between runs. U_{max} then decreased in line with the sediment supply rate
309 to approximately 0.97 m s^{-1} in run 5 (UVPs 1 and 2). This trend of increasing then decreasing flow
310 velocity with sediment supply rate was also documented on the basin floor (UVPs 5-8). Uncertainty is
311 attached to the later (e.g. run 5) basin floor readings as the highly variable flow pathways created by
312 the depositional topography (see Figure 4A) hindered the probes' ability to accurately record the
313 dominant flow direction. Despite this uncertainty, the broad trends of increasing velocities with
314 increasing sediment supply rate were consistent across the slope and basin floor (Figure 5). This flow-
315 field evolution correlates with the depositional trend of a forward then back-stepping depositional
316 system, demonstrating a clear link between process and product.



317

318 **FIGURE 5** Time-averaged velocity profiles for runs 1 – 5 (A-E). Measurements taken along the centre of the channel and
 319 across the break of slope (Figure 2 for location). Solid lines represent UVPs on the slope and dashed-dotted lines represent
 320 UVPs on the basin floor. Velocity averages were taken for entire run durations, minus the head and tail of each flow (first
 321 and last five seconds).

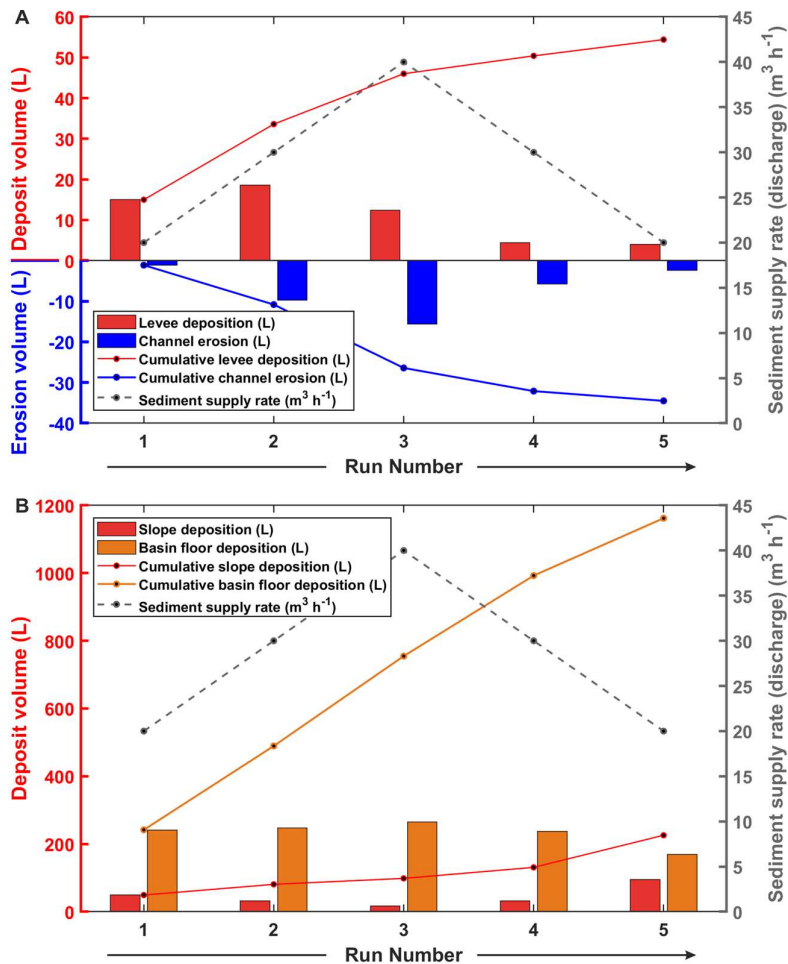
322 4 DISCUSSION

323 4.1 Expression of external signals and internal processes in submarine fan 324 environments

325 4.1.1 External versus internal controls on slope channels

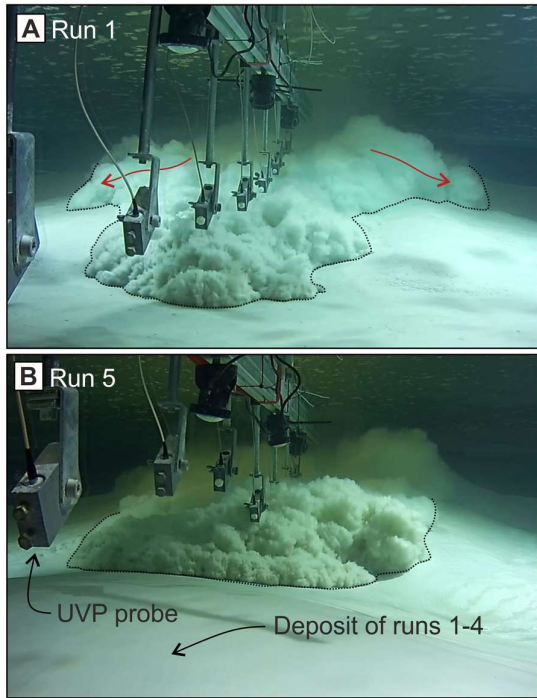
326 External factors, in this case a waxing-to-waning sediment supply rate, set the initial boundary
 327 conditions for submarine fan development. These external drivers (e.g. tectonics, sea level, and
 328 climate) promote conditions whereby sediment delivery may be more (or less) likely and can create
 329 or remove accommodation for sediment deposition (King et al., 2009; Clare et al., 2016; Harris et al.,
 330 2016; Allin et al., 2018). In this experiment, sediment supply rate was the primary control on the
 331 amount of erosion/deposition that occurred within the slope-channel. Low sediment supply rates
 332 resulted in relatively high amounts of deposition within the channel and vice-versa (Figure 6). The
 333 volume of overbank (levee) deposition in runs 1 to 3 stayed relatively high (> 10 litres (L) for each run)
 334 as sediment supply rate increased, despite the channel being progressively widened and deepened by
 335 channel erosion and overbank deposition (Figures 4B and 6; Supporting Figure 1). These growing
 336 levees would normally be predicted to progressively confine the flows due to the flows becoming

337 smaller with respect to the channel form (Hodgson et al., 2016; Shumaker et al. 2018). Instead, the
 338 levees continued to be overtopped; probably due to flows becoming progressively larger, experiencing
 339 more turbulent mixing and decreased grain-size stratification as the sediment supply rate was
 340 increased between runs (Rouse, 1939; Kneller and McCaffrey, 1999; de Leeuw et al., 2018a;
 341 Eggenhuisen et al., 2019). When sediment supply rate was reduced, overbank deposition lessened (<
 342 5 L in each run) and deposition in the channel axis increased as the flows of runs 4 and 5 were now
 343 substantially underfit with respect to the new evolved channel dimensions (Figures 6 and 7; de Leeuw
 344 et al., 2018b). As the incoming flow conditions for runs 1 and 5 were identical, the decrease in
 345 overbank deposition in run 5 is likely due to increased erosional and constrictional confinement
 346 (Figures 4B and 6; Supporting Figure 1). This is more in line with the convention whereby channels in
 347 disequilibrium work towards an idealised geometry as the experimental flows latterly experienced
 348 reduced overbank deposition, predominantly depositing within the channel (Figures 6 and 7; Kneller
 349 et al. 2003; Hodgson et al., 2016; Shumaker et al. 2018). Previous studies have identified similar
 350 depositional trends to those observed here in channel-levee outcrops and attributed them to either
 351 external variation of flow magnitude, or the internal processes of overbank aggradation and sediment
 352 transfer through the channel (Kane and Hodgson, 2011). This study suggests that not only are these
 353 scenarios plausible, but also that both processes may act upon the system concurrently. Rather than
 354 progressively less sediment being overspilled with each run through the experiment, we observed
 355 consistently high amounts of overspill in the waxing phase which abruptly declined in the waning
 356 phase (Figure 6). This newly documented evolution is driven by the interplay of sediment supply rate
 357 (external) and constrictional/erosional channel confinement mechanisms (internal).



358

359 **FIGURE 6** Progression of deposition and erosion volume across the five runs. (A) Levee deposition (area of volume
 360 calculation outlined in Supporting Figure 1) versus channel erosion. In the waxing phase of sediment supply rate (runs 1-3),
 361 the volume deposited by each run was maintained at a relatively high level (> 10 L/run). In the waning phase (runs 4 and 5)
 362 levee deposition was markedly reduced (< 5 L/run). Erosion volume for each run increased and decreased in line with
 363 sediment supply rate. The excessive erosion at the inlet box was excluded from the calculation. (B) Slope deposition versus
 364 basin floor deposition. Whole slope deposition showed an inverse relationship with sediment supply rate. Most of the slope
 365 deposition in runs 1, 4, and 5 occurred within the channel axis. Basin floor deposition decreased by 68 L in run 5. This is
 366 associated with a marked increase in slope deposition as the basinal deposit back-stepped onto the slope.



367 **FIGURE 7** Photos of turbidity currents from runs 1 (A) and 5 (B) as they reached the break of slope, just prior to loss of
 368 channel confinement. Runs 1 and 5 represented the beginning and end of the waxing-to-waning sediment supply and had
 369 the same sediment supply rate ($30 \text{ m}^3 \text{ h}^{-1}$). Flow direction was towards the camera. The currents are outlined with a dotted
 370 black line for clarity. For scale, UVPs are spaced at 40 cm intervals. (A) The current of run 1 overspilled the channel on either
 371 side as indicated by the red arrows. (B) The current of run 5 is almost entirely contained within the widened and deepened
 372 channel.
 373

374 Comparable experiments of de Leeuw et al. (2018a) demonstrated that submarine channel evolution
 375 is a function of both levee growth and channel floor aggradation/degradation, and that fining upwards
 376 grain-size trends in levees need not necessarily reflect external forcing. This trend of constructional
 377 and erosional confinement has also been documented in various recent and ancient datasets (e.g.
 378 Deptuck et al., 2007; Janocko et al., 2013; Hodgson et al., 2016; Kneller et al., 2020). Previous research
 379 has shown similar findings in different depositional settings such as alluvial fans and river deltas where
 380 overbank flow, cut-through, and back-filling of channels play an important role (e.g. Hoyal and Sheets,
 381 2009; Hamilton et al., 2013; de Haas et al., 2016). Our findings agree with these previous studies but
 382 also suggest that external forcing can directly influence the rate, timing, and distribution of erosion
 383 and deposition in submarine channel-levee systems.

384 The increase in flow confinement within the slope channel documented in runs 1-3 of our experiments
 385 improved the channel's efficiency at bypassing sediment to the basin floor (de Leeuw et al., 2018b),
 386 but not to the same extent as the external signal of increasing sediment supply rate. De Leeuw et al.
 387 (2018b) showed using a similar experimental set-up that a narrower and deeper channel promotes

388 greater flow thickness and velocity. They documented an increase in flow velocity of $\sim 0.03 \text{ m s}^{-1}$ when
389 the channel width was dropped from 1.2 to 0.53 m. This is approximately 9 times less than the velocity
390 increase we document between runs 1-3 in our study (0.27 m s^{-1} at UVP 2), indicating that the external
391 signal of sediment supply rate was the dominant control on the flow field evolution.

392 It is possible that by altering the pattern of sediment supply to the experimental system from flows
393 with quasi-steady sediment supply rate that incrementally increased between runs, to flows that also
394 had internal sediment supply rate variability (i.e. 2nd order supply cycles) that sediment distribution in
395 the basin would be affected. However, physical and numerical experiments by Li et al. (2016) and
396 Foreman and Straub (2017) on deltaic and alluvial systems suggest that external controls (they use
397 relative sea-level and climate oscillation respectively) had to be of a greater spatial and temporal scale
398 than that of the internal dynamics of the system. This suggests that smaller-scale variation than that
399 applied to this experimental system may be undetectable in the depositional record, particularly in
400 increasingly distal settings. Supporting this, recorded discharge rates in our experiments show varying
401 amounts of deviation from the reference discharge values (sediment supply rate) but there is no
402 evidence of this small-scale variability in the resultant deposits (Figure 3).

403 4.1.2 External versus internal controls on basin floor deposition

404 Meanwhile on the basin floor, an entirely different signature was left by the interaction of external
405 and internal controls. In the waxing phase of sediment supply, increased flow velocities enabled flows
406 to transport sediment progressively farther into the basin (Figure 4; Sychala et al., 2019). If sediment
407 supply rate had not been increased between runs, it is possible that the basin floor deposits would
408 not have forward stepped to the same extent. Using a similar experimental set-up with constant
409 sediment supply rate, Fernandez et al. (2014) showed that lobes deposited across a slope break
410 immediately back-step, never extending beyond the initial deposit. In our experiments, increasing flow
411 confinement on the slope partially increased the flow's ability to transport sediment basinwards
412 (Figure 4B, cross-section A-A'; de Leeuw et al. 2018b), enhancing the external signal of increasing
413 sediment supply rate. This internal slope process was masked in the waning phase of the series (runs
414 4 and 5) by abrupt back-stepping of the basin floor deposits, comparable to channel back-filling
415 documented by Hoyal and Sheets (2009) in a deltaic experimental setting. During the waning phase,
416 internal depositional relief reduced the local slope gradient to the point where it became horizontal
417 and even adverse to the main slope gradient. This alteration of the basinal topography enhanced the
418 back-stepping trend of the waning phase by reducing flow velocities earlier in the basin and promoting
419 increased slope deposition (Figure 6B). The back-stepping trend features a more pronounced shift in
420 depositional loci than the initial forward-stepping trend (Figure 4 and Supporting Figure 1). As such, it
421 is likely that the effect of the depositional relief was strong enough to force back-stepping of the
422 system irrespective of lowering sediment supply rate. This is supported by the observation of
423 immediate back-stepping in Fernandez et al.'s (2014) experiments with constant sediment supply. It
424 is therefore insinuated that internal forcing on the basin floor assumed a progressively larger role in
425 deposit distribution relative to external forcing. Regardless of the sediment supply signal, internal
426 organisation through lobe compensation, depositional topography and consequent back-stepping
427 pervades as a dominant feature on the basin floor, supporting the observations of previous studies
428 (e.g. Cantelli et al., 2011; Fernandez et al., 2014; Burgess et al. 2019).

429 4.1.3 Comparison of slope versus basin floor environments

430 The implication behind the above findings is that the roles of both external and internal forces are
431 contrasting depending on the position along the depositional profile and the temporal stage of the
432 submarine fan's development. These findings are comparable to those of Allin et al. (2018) who

433 showed how an external signal propagated by sea-level cycles becomes progressively less clear from
434 proximal to distal in the Nazaré depositional system. Within the slope channel environment of our
435 experiments, we observed an amplification of the external signal by progressive flow confinement,
436 promoting sediment deposition deeper in the basin. Concurrently on the basin floor, internally
437 induced compensational stacking and depositional relief augmented the external signal to the point
438 of forcing abrupt and pronounced back-stepping towards the latter half of the series (Figure 4).
439 Deposits from nominally identical input conditions in the waxing and waning limbs of supply cycles
440 are therefore very different. This is reflected in the recorded velocity profiles which show highly
441 variable time-averaged flow velocities in run 5 compared to run 1, presumably due to the evolved
442 channel dimensions and complex depositional topography (Figure 5).

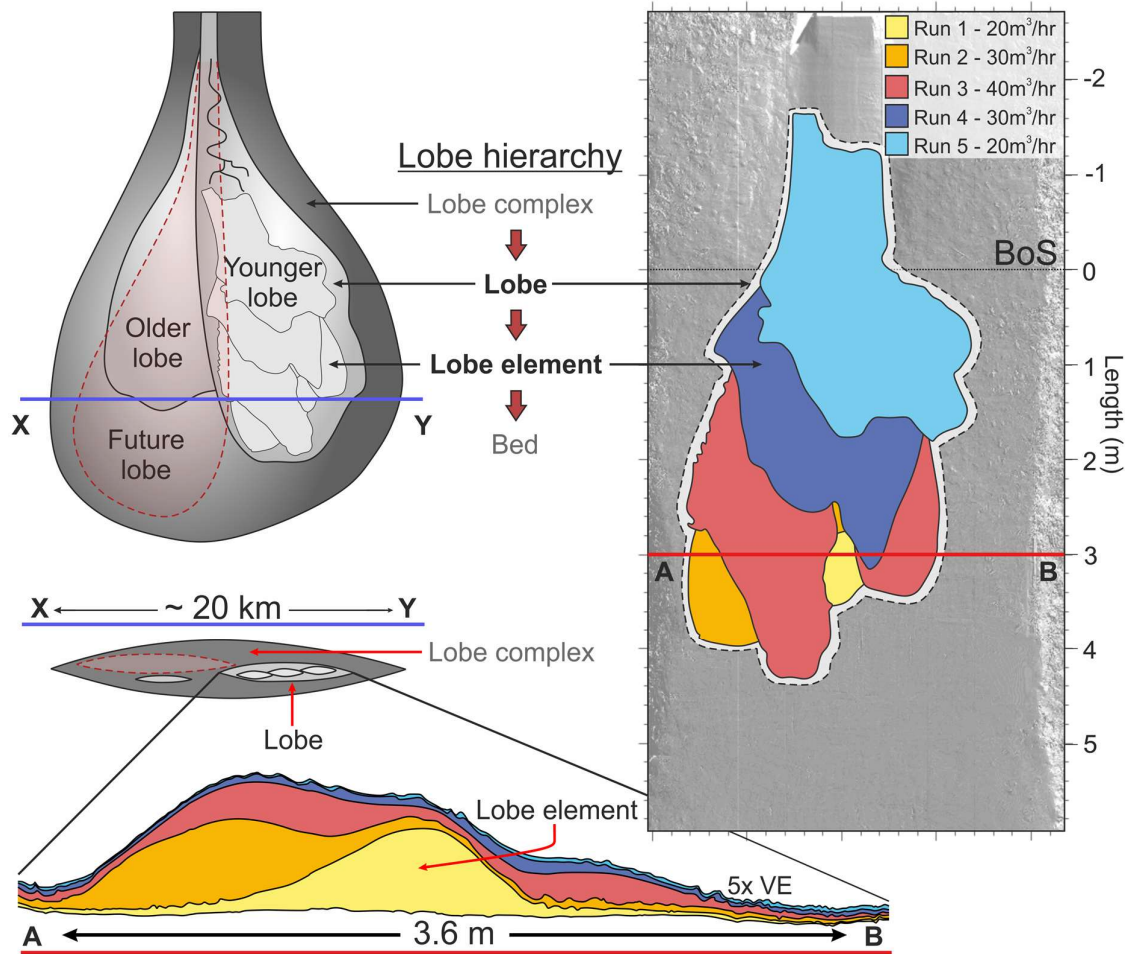
443 Compensational stacking and back-stepping through time as seen here has been documented similarly
444 in modern seafloor (Deptuck et al., 2008; Prather et al., 2012; Jobe et al., 2017), experimental (Cantelli
445 et al., 2011; Fernandez et al., 2014), and numerical (Burgess et al., 2019) data sets. The results of this
446 study build upon these previous works, indicating that when external factors (in this case waxing-to-
447 waning sediment supply rate) are present they have a stronger influence upon channels, whilst basin
448 floor deposition is dominated primarily by internal processes. It is possible that by testing a wider
449 range of boundary conditions (e.g. different grain sizes, channel slope/width/depth) that other styles
450 of external forcing may be represented. This may express the relationship between external and
451 internal controls on submarine slopes and basin floors subtly differently. Fortunately, the effect of
452 different boundary conditions has been evaluated in previous works (de Leeuw et al., 2018b; Sychala
453 et al., 2019). For example, de Leeuw et al. (2018b) demonstrated how channels with low width:depth
454 ratios bypass sediment more efficiently to the basin floor than channels with high width:depth ratios.
455 These findings support the broad trends of submarine fan development documented herein,
456 suggesting that examining external forces by varying different boundary conditions may produce
457 largely similar results.

458 External factors having a stronger impact upon slope channel-levees than basin floor depositional
459 environments has substantial implications. Whilst levees are commonly well-preserved, the channel
460 axis has inherently lower preservation potential than basin floor deposits. The deposits of smaller-
461 scale turbidity currents within the channel are known to be ‘flushed’ out the channel system by larger
462 flows, removing stratigraphy (Allin et al., 2018; Jobe et al., 2018). Consequently, there is a high risk
463 that the channel-fill deposits that contain the record of the external signal are not preserved in the
464 rock record. If we take the channel-fill deposits of our experiments for example, we record only the
465 deposits associated with back-filling and nothing of the erosive runs 1-3 that came before (Figure 4B;
466 cross-section A-A’). Only with our high-resolution data set are we able to identify the complex
467 relationship between the channel axis and levees through time and attribute this to external and
468 internal factors (Section 4.1.1). In natural modern and ancient datasets, extracting explicit information
469 to differentiate between external and internal mechanisms within slope channels will continue to be
470 challenge due to resolution issues. By investigating modern systems with repeat monitoring over short
471 time-scales the degree of preservation within the channel axis may be more confidently resolved. In
472 contrast, basin floor deposits in natural settings do not record smaller turbidity currents that fail to
473 reach them, but their preservation potential is substantially higher than channels due to the
474 predominantly depositional nature of basin floor environments.

475 Our results suggest that whilst slope channel-levees may provide the best record of external signals,
476 they have low preservation potential in the channel axis. Meanwhile basin floor lobes feature a lower
477 resolution record of external signals, but a better-preserved depositional record. Section 4.3 provides

478 a possible mechanism whereby we may still be able to use this limited rock record in tandem with the
 479 observations of this study to interpret stacking patterns in outcrop and core.

480 **4.2 Hierarchy of basin floor depositional elements**



481
 482 **FIGURE 8** Experimental deposits placed within a hierarchical scheme for lobe deposits. Modified from (Groenenberg et al.,
 483 2010). Whilst the deposits from each run constituted a single flow event and were therefore technically ‘beds’ by the strictest
 484 definition, they bore a closer architectural resemblance to ‘lobe elements’ (Prélat et al., 2009), with pronounced
 485 compensational stacking (Straub and Pyles, 2012) and classical lobate shape. This has aided comparison to larger-scale
 486 natural systems. The plan-view image of the experimental ‘lobe’ displays the main deposit of the lobe elements (> 10 mm
 487 thick) whilst the corresponding colour-coded cross-section displays the entire lobe thickness, including the thin fringes of
 488 later lobe elements deposited in runs 4 and 5. The ‘future lobe’ indicated by the dashed red line on the natural-scale system
 489 extends farther into the basin to represent hypothetical progradation of the lobe complex. BoS = break of slope.

490 Basin floor lobe deposits have been recognised as hierarchical in nature due to their compensational
 491 stacking (Deptuck et al., 2008; Prélat et al., 2009; Straub and Pyles, 2012; Grundvåg et al., 2014; Jobe
 492 et al., 2017). To assist comparison between the experimental deposits of this study and those of larger-scale
 493 natural submarine fan systems, the lobe deposit hierarchy of Prélat et al. (2009) is used (Figure
 494 8). This scheme consists of four components: one or more ‘beds’ -the product of individual flow
 495 events- stack to form a ‘lobe element’. Lobe elements are generally a few kilometres in length and
 496 width and a few metres thick (Prélat et al., 2010). One or more lobe elements fed from a single channel
 497 stack to form a ‘lobe’. An updip avulsion or migration of the channel creates a new lobe, stacking on
 498 top of the earlier lobe to form a ‘lobe complex’. Whilst the individual runs of this study were individual
 499 flow events and so were technically beds by the above definition, the key aim was to represent a

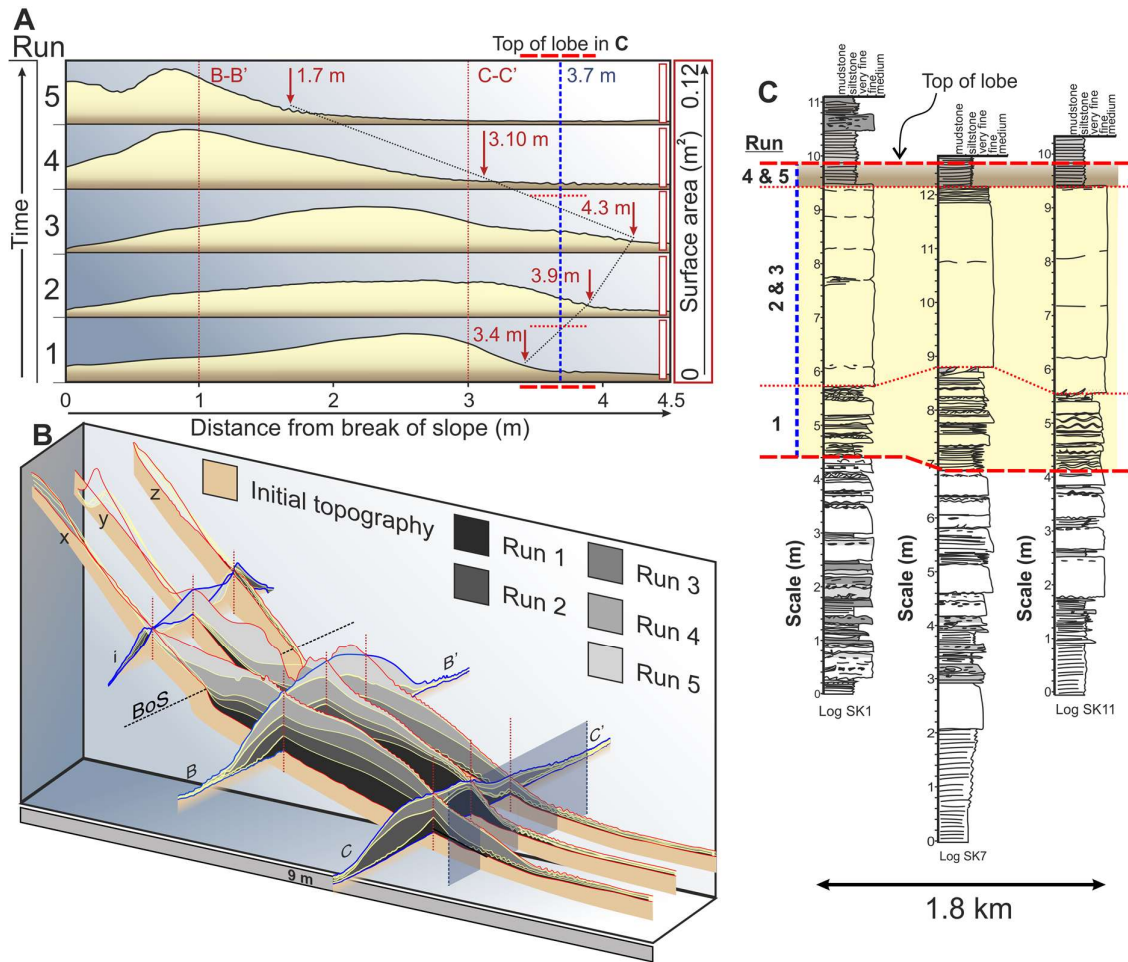
500 protracted phase of waxing-to-waning sediment supply to a submarine fan over geological time. This
501 would be very difficult to resolve by considering five flow events in isolation. Each run of this study is
502 consequently considered to represent a lobe element, with the whole series of runs representing a
503 lobe (*sensu* Spychala et al., 2019). This approach is further supported by evidence that beds stack more
504 aggradationally relative to lobe elements which show more pronounced compensation (Straub and
505 Pyles et al., 2012). Jobe et al. (2017) effectively show how bed-scale deposits can still display
506 compensation in modern intraslope settings, however, the compensation recorded in these
507 experiments is substantially more pronounced than that of the beds recorded in the western Niger
508 Delta slope.

509 Despite the usefulness of comparing our data to hierarchical schemes of natural systems, doing so
510 highlights some of the difficulty in applying strict organisational structure to nature. In the transition
511 between the channel and lobe in our experiment, the deposition is clustered or ‘anti-compensational’
512 across all five runs (Figure 4B, cross-section B-B’), with the deposits stacking on top of each other
513 (Straub et al., 2009). This aggradational character is likely due to the channel position effectively
514 controlling the depositional location. Therefore, compensation does not appear able to develop until
515 a distance down-dip from the channel-lobe transition (Figure 4B, cross-section C-C’, and Figure 8).

516 If the simplified view is taken that discrete ‘hierarchical components’ (i.e. bed-sets, lobe elements,
517 lobes, and lobe complexes) are internally composed of clustered units, at the break of slope in our
518 study there was only a single hierarchical component. There was no deposit compensation at this
519 location (Figure 4B, cross-section B-B’), implying that multiple lobe elements did not exist there. If we
520 take this to be true, the hierarchical component becomes more of a local geometric definition rather
521 than a hierarchically delineated correlatable unit. This raises fundamental questions about
522 depositional hierarchy and its spatial applicability. For example, how do hierarchical components vary
523 in their geometry from proximal to distal and what are the implications for their practical application?
524 Our results suggest that lobe element-scale strata may be more challenging to distinguish near the
525 channel to lobe transition where deposits behave more aggradationally, versus the lobe fringe where
526 compensation is common.

527 4.3 Implications for interpretation of submarine fan records

528 The evolution from forward-stepping and compensational stacking, to abrupt back-stepping recorded
529 in this experimental fan can be used as a possible explanation for bed stacking patterns commonly
530 observed in outcrop and subsurface-cores from examples in the rock record. A thickening- and
531 coarsening-upwards trend in submarine lobe deposits has been described from several outcrops and
532 this is often followed by an abrupt transition to thin-bedded fine grained sediments, usually
533 interpreted as hemipelagic abandonment or distal fringe facies (Pickering, 1983; Grecula et al., 2003;
534 Bernhardt et al., 2011; Macdonald et al., 2011). The coarsening- and thickening-upwards succession
535 is typically attributed to the local depositional environment becoming progressively higher in energy,
536 transitioning from marginal to more axial fan localities (Kane and Pontén, 2012). However, the forcing
537 mechanism for the abrupt transition from thick sandstones to packages of fine-grained sediments is
538 less clearly understood. We argue that the evolution of the ‘experimental lobe’ in this study provides
539 an elegant way to explain this stacking pattern. Figure 9 shows the temporal evolution of the
540 experimental lobe in both 2D and 3D space. The 2D diagram (Figure 9A) displays the forward and back-
541 stepping of the lobe from run 1 to 5, by showing how the location of the maximum deposit volume
542 shifts in a dip-oriented direction through time. The 3D cross-sectional diagram (Figure 9B) emphasises



543

544 **FIGURE 9** Interpreting deposit stacking patterns in nature using experimental observations. (A) Variation in deposit volume
 545 with distance from the break of slope for each run. Cross-sectional surface area is used as a proxy for deposit volume by
 546 calculating the difference between pre- and post-run topography with high resolution (every 2 mm) perpendicular to the
 547 dominant slope (Spychala et al. 2019). Red arrows indicate the distal end of axial deposits (values taken from DEMs in Figure
 548 2). The dashed blue line and cross-cutting dashed/dotted red lines are representative of the corresponding lines in c. Cross-
 549 section intersections are indicated by vertical dashed red lines. (B) Internal architecture of the cumulative deposit
 550 represented in three-dimensional space using composite cross-sections (see Figure 4B). Deposit fore- and back-stepping,
 551 as well as lateral shifting, can be observed. The semi-transparent blue panel is representative of the dashed blue line in (C). (C)
 552 Comparative sedimentary logs from the outcropping Fan 3 of the Skoorsteenberg Formation, Karoo Basin, South Africa
 553 (modified from Kane et al., 2017). The yellow shaded interval highlights older interpretations (e.g. Pr elat et al., 2009; Kane
 554 et al., 2017) of 'Lobe 5' whilst here we reinterpret the top of the lobe as within the thin-bedded, fine-grained deposits above
 555 this sandstone. The accompanying dashed blue line is depicted in both (A) and (B) (as a semi-transparent blue panel) to
 556 indicate the outcrop's comparative position on the experimental deposit. The abrupt back-stepping in this model could
 557 explain the abrupt facies changes commonly observed in outcrop and core at lobe-scale.

558 the internal complexity of the lobe, particularly how lobe element compensation is more pronounced
 559 distally. Supporting these images is a series of sedimentary logs from Fan 3 of the Permian
 560 Skoorsteenberg Formation, Karoo Basin, South Africa (Figure 9C; Kane et al., 2017). The highlighted
 561 zone on these logs indicates 'Lobe 5', a typical example of this coarsening and thickening trend that
 562 abruptly reverts to siltstone. Conventionally, the siltstone at the top of the sandstone has been
 563 interpreted to represent one of two models: 1) A condensed section of hemipelagic deposition during
 564 an externally driven reduction in sediment supply (Johnson et al., 2001; Hodgson et al., 2006); 2)
 565 Lateral fringes of additional lobes, representing system-internal lobe-scale compensation (Pr elat et
 566 al., 2009). Recent studies are beginning to challenge the notion that mud deposition within active

567 submarine fan systems is purely hemipelagic in nature, more likely representing the distal fringe of
568 active systems (Boulesteix et al., 2019). This suggests it is unlikely that the siltstones above the lobe 5
569 sandstones are reflecting a complete 'shutdown' of sediment supply. The model of lateral fringe
570 aggradation of later lobes is more likely due to widely recognised compensational stacking and
571 associated grain-size distributions in lobe deposits (Deptuck et al., 2008; Pr lat et al., 2009; Straub and
572 Pyles, 2012). However, this does not explain the abruptness at which deposits transition to fine-
573 grained sediments (Figure 9C). We propose an adapted version of this model whereby this transition
574 can be more readily explained by a combination of compensational stacking *and* rapid back-stepping
575 of 'lobe elements' (Figures 8 and 9). It is suggested that depositional relief and waning sediment supply
576 as is observed in our experiments drives this evolution, leading to the stratigraphic patterns we
577 observe in nature.

578 Identification of back-stepping deposits from compensationally lateral-stepping deposits will always
579 be challenging in outcrop and core due to the likelihood of similar facies being present in distal along-
580 axis and off-axis trends. Differentiating criteria for back-stepping deposits would include: a) abrupt
581 vertical transition from sand-dominated to mud dominated facies; b) beds that thin across-strike in
582 both directions, rather than thickening laterally into an adjacent lobe axis; and c) a preference for
583 deposition of hybrid event beds relative to ripple-laminated deposits. Hybrid event beds have been
584 documented to characterise deposition in frontal fringe environments where we might expect to
585 observe back-stepping, whilst ripple-laminated deposits show preference for the lateral fringe
586 (Spychala et al., 2017). Identifying any or even all of these criteria would not mean unequivocal proof
587 for back-stepping due additional basinal complexity such as complex regional topography, however,
588 they would provide the basis for assessment of submarine fan evolution when considered within the
589 context of the regional picture. Identification of abruptly back-stepping strata in the rock record of
590 any given system would have implications for our understanding of the distribution of sediment within
591 that basin. If strata are identified as abruptly back-stepping, this suggests that the system may have
592 built depositional relief to the point of forcing the system backwards irrespective of external sediment
593 supply, perhaps due to a degree of (scale-dependent) basin confinement. If no evidence for abrupt
594 back-stepping is observed, this may imply that incoming flows have had space to continue to stack
595 compensationally until sediment supply has waned, allowing for a more 'classic' gradational upwards
596 transition to fine grained deposits.

597 Previous workers placed the top of Lobe 5 (Figure 9C) at the top of the thick sandstone unit (Pr lat et
598 al., 2009; Kane et al., 2017). However, this study suggests that that the top of the lobe (i.e. the end of
599 the sedimentary cycle) at a fixed point within the system is not necessarily where the thickest/coarsest
600 deposits are observed but may lie within the fine-grained deposits above (Figure 9C). Unlike muddy
601 channel bases, which typically have erosive surfaces to demark them (Hubbard et al., 2014), confident
602 identification the exact top of the lobe within fine-grained deposits would be challenging. When no
603 erosion is apparent, the deposits from the top of one lobe would likely transition into the base of the
604 next with no recognisable change in sedimentary facies. Despite this, these findings prove useful in
605 highlighting the bias of previous lobe deposit studies towards sandier intervals and call for a
606 reassessment of where we interpret the tops and bases of hierarchical units within submarine fans
607 (Spychala et al., 2019).

608 **5 CONCLUSIONS**

609 Using physical models with a signature of waxing-to-waning sediment supply, the interplay of external
610 signals with internal processes within submarine fans has been evaluated. On the channelised slope,
611 increasing sediment supply rate resulted in increased channel erosion and overbank deposition. The
612 evolved channel dimensions improved flow efficiency, enhancing the external signal on the slope.
613 Concurrently on the basin floor, increasing sediment supply rate led to forward-stepping of lobe
614 elements, however this was partially obscured by internal reorganisation through compensational
615 deposit stacking. When sediment supply rate was subsequently reduced, basin floor deposits back-
616 stepped abruptly due to depositional relief to onlap the slope and infill the slope channel. Flows were
617 then underfit with respect to the evolved channel dimensions and confined within the widened and
618 deepened channel. Consequently, limited overbank deposition took place in the waning phase of
619 sediment supply. This complex overall evolution resulted in deposits that were distinctly different in
620 the waxing and waning phases of sediment supply, despite similar external input conditions.

621 A comparison of the slope and basin floor environments revealed that external factors have a
622 stronger influence upon slope channels whilst internal processes dominate basin floor lobe deposits.
623 These findings validate many conceptual models of submarine fans, including sediment supply driven
624 progressive channel confinement, and how internal reorganisation can shred external signals in the
625 deepest parts of the sedimentary sink. Despite this internal 'dilution' of the external signal and the
626 poorer preservation potential of deposits in the slope channel axis, the external signal could still be
627 observed on the basin floor, with deposits from higher sediment supply rates extending farther into
628 the basin before depositional relief dominated.

629 The recorded evolution of forward-stepping and compensation followed by abrupt back-stepping
630 represents the signature of an entangled external-internal cycle of sedimentation in a submarine
631 fan. This evolution is a possible new mechanism to explain common vertical stacking patterns of
632 coarsening and thickening upwards sandstone successions followed abruptly by thin-bedded fine-
633 grained sediment in outcrop and core. These findings should encourage continued analysis of
634 submarine fan architecture from a perspective that integrates both external and internal controlling
635 mechanisms and provide a new evolutionary model to search for in natural systems. Future work
636 may aim to test a range of different external signals such as variable sediment concentration or grain
637 size to assess whether these have a different impact on the organisation of submarine fans.

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644 **CONFLICT OF INTEREST**

645 The authors have no conflict of interest to declare.

646 **DATA AVAILABILITY STATEMENT**

647 The data that support the findings of this study are available as supporting information. Any additional
648 data requests can be made to the corresponding author.

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651 **REFERENCES**

- 652 Allin, J.R., Hunt, J.E., Clare, M.A. and Talling, P.J. (2018). Eustatic sea-level controls on the flushing
653 of a shelf-incising submarine canyon. *GSA Bulletin*, 130, 222-237.
654 <https://doi.org/10.1130/B31658.1>.
- 655 Azpiroz-Zabala, M., Cartigny, M.J.B., Talling, P.J., Parsons, D.R., Sumner, E.J., Clare, M.A. et al.
656 (2017). Newly recognized turbidity current structure can explain prolonged flushing of
657 submarine canyons. *Science Advances*, 3, 1-12. <https://doi.org/10.1126/sciadv.1700200>.
- 658 Beerbower, J.R. (1964). Cyclothems and cyclic depositional mechanisms in alluvial plain
659 sedimentation. *Kansas State Geological Survey Bulletin*, 169, 31-42.
- 660 Bernhardt, A., Jobe, Z.R. and Lowe, D.R. (2011). Stratigraphic evolution of a submarine channel-
661 lobe complex system in a narrow fairway within the Magallanes foreland basin, Cerro Toro
662 Formation, southern Chile. *Marine and petroleum Geology*, 28, 785-806.
663 <https://doi.org/10.1016/j.marpetgeo.2010.05.013>.
- 664 Bernhardt, A., Melnick, D., Hebbeln, D., Lückge, A. and Strecker, M.R. (2015). Turbidite
665 paleoseismology along the active continental margin of Chile—Feasible or not? *Quaternary*
666 *Science Reviews*, 120, 71-92. <https://doi.org/10.1016/j.quascirev.2015.04.001>.
- 667 Blum, M., Rogers, K., Gleason, J., Najman, Yani, Cruz, J. and Fox, L. (2018). Allogenic and Autogenic
668 Signals in the Stratigraphic Record of the Deep-Sea Bengal Fan. *Scientific Reports*, 8, 7973.
669 <https://doi.org/10.1038/s41598-018-25819-5>.
- 670 Boulesteix, K., Poyatos-Moré, M., Flint, S.S., Taylor, K.G., Hodgson, D.M. and Hasiotis, S.T. (2019).
671 Transport and deposition of mud in deep-water environments: Processes and stratigraphic
672 implications. *Sedimentology*, 1-32. <https://doi.org/10.1111/sed.12614>.
- 673 Burgess, P.M., Masiero, I., Toby, S.C. and Duller, R.A. (2019). A big fan of signals? Exploring
674 autogenic and allogenic process and product in a numerical stratigraphic forward model of
675 submarine-fan development. *Journal of Sedimentary Research*, 89, 1-12.
676 <https://doi.org/10.2110/jsr.2019.3>.
- 677 Cantelli, A., Pirmez, C., Johnson, S. and Parker, G. (2011). Morphodynamic and stratigraphic
678 evolution of self-channelized subaqueous fans emplaced by turbidity currents. *Journal of*
679 *Sedimentary Research*, 81, 233-247. <https://doi.org/10.2110/jsr.2011.20>.
- 680 Cecil, C.B. (2003). The concept of autocyclic and allocyclic controls on sedimentation and
681 stratigraphy, emphasising the climatic variable. In Cecil C.B. and Edgar, N.T. (eds.), *Climate*

- 682 *Controls on Stratigraphy. SEPM Special Publications, 77, 13-20.*
683 <https://doi.org/10.2110/pec.03.77.0013>.
- 684 Clare, M.A., Talling, P.J., Challenor, P., Malgesini, G. and Hunt, J. (2014). Distal turbidites reveal a
685 common distribution for large (> 0.1 km³) submarine landslide recurrence. *Geology*, 42, 262-
686 266. <https://doi.org/10.1130/G35160.1>.
- 687 Covault, J.A., Romans, B.W., Fildani, A., McGann, M., and Graham, S.A. (2010). Rapid Climatic
688 Signal Propagation from Source to Sink in a Southern California Sediment-Routing System. *The*
689 *Journal of Geology*, 118, 247–259. <https://doi.org/10.1086/651539>.
- 690 Covault, J.A., Romans, B.W., Graham, S.A., Fildani, A., and Hilley, G.E. (2011). Terrestrial source to
691 deep-sea sink sediment budgets at high and low sea levels: Insights from tectonically active
692 Southern California. *Geology*, 39, 619–622. <https://doi.org/10.1130/G31801.1>.
- 693 de Haas, T., van den Berg, W., Braat, L. and Kleinhans, M.G. (2016). Autogenic avulsion,
694 channelization and backfilling dynamics of debris-flow fans. *Sedimentology*, 63(6), 1596-1619.
- 695 de Leeuw, J., Eggenhuisen, J.T. and Cartigny, M.J.B. (2016). Morphodynamics of submarine
696 channel inception revealed by new experimental approach. *Nature Communications*, 7, 10886.
697 <https://doi.org/10.1038/ncomms10886>.
- 698 de Leeuw, J., Eggenhuisen, J.T. and Cartigny, M.J.B. (2018a). Linking submarine channel–levee
699 facies and architecture to flow structure of turbidity currents: insights from flume tank
700 experiments. *Sedimentology*, 65, 931-951. <https://doi.org/10.1111/sed.12411>.
- 701 de Leeuw, J., Eggenhuisen, J.T., Spychala, Y.T., Heijnen, M.S., Pohl, F., Cartigny, M.J.B. (2018b).
702 Sediment volume and grain-size partitioning between submarine channel–levee systems and
703 lobes: an experimental study. *Journal of Sedimentary Research*, 88, 777-794.
704 <https://doi.org/10.2110/jsr.2018.46>.
- 705 Deptuck, M.E., Sylvester, Z., Pirmez, C. and O’Byrne, C. (2007) Migration–aggradation history and
706 3-D seismic geomorphology of submarine channels in the Pleistocene Benin–major Canyon,
707 western Niger Delta slope. *Marine and Petroleum Geology*, 23, 406-433.
708 <https://doi.org/10.1016/j.marpetgeo.2007.01.005>.
- 709 Deptuck, M.E., Piper, D.J.W., Savoye, B. and Gervais, A. (2008). Dimensions and architecture of
710 late Pleistocene submarine lobes off the northern margin of East Corsica. *Sedimentology*, 55,
711 869-898. <https://doi.org/10.1111/j.1365-3091.2007.00926.x>.
- 712 Dorrell, R. M., Burns, A. D. and McCaffrey, W. D. (2015). The inherent instability of leveed seafloor
713 channels. *Geophysical Research Letters*, 42(10), 4023-4031.
714 <https://doi.org/10.1002/2015GL063809>.
- 715 Emmel, F.J. and Curray, J.R. (1983). The Bengal submarine fan, northeastern Indian Ocean. *Geo-*
716 *Marine Letters*, 3, 119-124. <https://doi.org/10.1007/BF02462456>.
- 717 Eggenhuisen, J.T., Tilston, M.C., de Leeuw, J., Pohl, F. and Cartigny, M.J.B. (2019). Turbulent
718 diffusion modelling of sediment in turbidity currents: An experimental validation of the Rouse
719 approach. *The Depositional Record*, 00, 1-14. <https://doi.org/10.1002/dep2.86>.
- 720 Fernandez, R.L., Cantelli, A., Pirmez, C., Sequeiros, O. and Parker, G. (2014). Growth patterns of
721 subaqueous depositional channel lobe systems developed over a basement with a downdip

- 722 break in slope: laboratory experiments. *Journal of Sedimentary Research*, 84, 168-182.
723 <http://dx.doi.org/10.2110/jsr.2014.10>.
- 724 Foreman, B.Z. and Straub, K.M., 2017. Autogenic geomorphic processes determine the resolution
725 and fidelity of terrestrial paleoclimate records. *Science advances*, 3, e1700683.
726 <https://doi.org/10.1126/sciadv.1700683>.
- 727 Grecula, M., Flint, S.S., De V. Wickens, H. and Johnson, S.D. (2003). Upward-thickening patterns
728 and lateral continuity of Permian sand-rich turbidite channel fills, Laingsburg Karoo, South
729 Africa. *Sedimentology*, 50, 831-853. <https://doi.org/10.1046/j.1365-3091.2003.00576.x>.
- 730 Groenenberg, R.M., Hodgson, D.M., Prélat, A., Luthi, S.M. and Flint, S.S. (2010). Flow-deposit
731 interaction in submarine lobes: Insights from outcrop observations and realizations of a
732 process-based numerical model. *Journal of Sedimentary Research*, 80, 252-267.
733 <https://doi.org/10.2110/jsr.2010.028>.
- 734 Grundvåg, S.A., Johannessen, E.P., Helland-Hansen, W. and Plink-Björklund, P. (2014).
735 Depositional architecture and evolution of progradationally stacked lobe complexes in the
736 Eocene Central Basin of Spitsbergen. *Sedimentology*, 61, 535-569.
737 <https://doi.org/10.1111/sed.12067>.
- 738 Gwiazda, R., Paull, C.K., Ussler, W. and Alexander, C.R. (2015). Evidence of modern fine-grained
739 sediment accumulation in the Monterey Fan from measurements of the pesticide DDT and its
740 metabolites. *Marine Geology*, 363, 125–133. <https://doi.org/10.1016/j.margeo.2015.02.006>.
- 741 Hamilton, P.B., Strom, K. and Hoyal, D.C. (2013). Autogenic incision-backfilling cycles and lobe
742 formation during the growth of alluvial fans with supercritical distributaries. *Sedimentology*,
743 60(6), 1498-1525 <https://doi.org/10.1111/sed.12046>.
- 744 Harris, A.D., Covault, J.A., Madof, A.S., Sun, T., Sylvester, Z. and Granjeon, D. (2016). Three-
745 dimensional numerical modeling of eustatic control on continental-margin sand distribution.
746 *Journal of Sedimentary Research*, 86, 1434-1443. <https://doi.org/10.2110/jsr.2016.85>.
- 747 Harris, A.D., Baumgardner, S.E., Sun, T. and Granjeon, D. (2018). A poor relationship between sea
748 level and deep-water sand delivery. *Sedimentary Geology*, 370, 42-51.
749 <https://doi.org/10.1016/j.sedgeo.2018.04.002>.
- 750 Hodgson, D.M., Flint, S.S., Hodgetts, D., Drinkwater, N.J., Johannessen, E.P. and Luthi, S.M. (2006).
751 Stratigraphic evolution of fine-grained submarine fan systems, Tanqua Depocenter, Karoo
752 Basin, South Africa. *Journal of Sedimentary Research*, 76, 20-40.
753 <https://doi.org/10.2110/jsr.2006.03>.
- 754 Hodgson, D.M., Kane, I.A., Flint, S.S., Brunt, R.L. and Ortiz-Karpf, A. (2016). Time-transgressive
755 confinement on the slope and the progradation of basin-floor fans: implications for the
756 sequence stratigraphy of deep-water deposits. *Journal of Sedimentary Research*, 86, 73-86.
757 <https://doi.org/10.2110/jsr.2016.3>.
- 758 Hoyal, D.C.J.D. and Sheets, B.A. (2009). Morphodynamic evolution of experimental cohesive
759 deltas. *Journal of Geophysical Research: Earth Surface*, 114, F02.
760 <https://doi.org/10.1029/2007JF000882>.
- 761 Hubbard, S.M., Covault, J.A., Fildani, A. and Romans, B.W. (2014). Sediment transfer and
762 deposition in slope channels: Deciphering the record of enigmatic deep-sea processes from
763 outcrop. *GSA Bulletin*, 126, 857-871. <https://doi.org/10.1130/B30996.1>.

- 764 Janocko, M., Cartigny, M.B.J., Nemeč, W., Hansen, E.W.M. (2013). Turbidity current hydraulics and
765 sediment deposition in erodible sinuous channels: Laboratory experiments and numerical
766 simulations. *Marine and Petroleum Geology*, 41, 222-249.
767 <https://doi.org/10.1016/j.marpetgeo.2012.08.012>.
- 768 Janocko, M., Nemeč, W., Henriksen, S., and Warchol, M. (2013). The diversity of deep-water
769 sinuous channel belts and slope valley-fill complexes. *Marine and Petroleum Geology*, 41, 7-34,
770 <https://doi.org/10.1016/j.marpetgeo.2012.06.012>. Jerolmack, D.J. and Paola, C. (2010).
771 Shredding of environmental signals by sediment transport. *Geophysical Research Letters*, 37,
772 L19401. <https://doi.org/10.1029/2010GL044638>.
- 773 Jobe, Z.R., Lowe, D.R. Uchytıl, S.J. (2011). Two fundamentally different types of submarine canyons
774 along the continental margin of Equatorial Guinea. *Marine and Petroleum Geology*, 28, 843-860.
775 <https://doi.org/10.1016/j.marpetgeo.2010.07.012>.
- 776 Jobe, Z.R., Sylvester, Z., Parker, A.O., Howes, N.C., Slowey, N., and Pirmez, C. (2015) Rapid
777 adjustment of submarine channel architecture to changes in sediment supply. *Journal of*
778 *Sedimentary Research*, 85, 729–753. <https://doi.org/10.2110/jsr.2015.30>.
- 779 Jobe, Z.R., Sylvester, Z., Howes, N., Pirmez, C., Parker, A., Cantelli, A. et al. (2017). High-resolution,
780 millennial-scale patterns of bed compensation on a sand-rich intraslope submarine fan, western
781 Niger Delta slope. *GSA Bulletin*, 129, 23–37. <https://doi.org/10.1130/B31440.1>
- 782 Jobe, Z.R., Howes, N., Romans, B.W. and Covault, J.A. (2018). Volume and recurrence of
783 submarine-fan-building turbidity currents. *The Depositional Record*, 4, 160-176.
784 <https://doi.org/10.1002/dep2.42>.
- 785 Johnson, S.D., Flint, S.S., Hinds, D., and De Ville Wickens, H. (2001). Anatomy of basin floor to slope
786 turbidite systems, Tanqua Karoo, South Africa. *Sedimentology*, 48, 987–1023.
787 <https://doi.org/10.1046/j.1365-3091.2001.00405.x>.
- 788 Kane, I.A., Kneller, B.C., Dykstra, M., Kassem, A. and McCaffrey, W.D. (2007). Anatomy of a
789 submarine channel-lee: An example from Upper Cretaceous slope sediments, Rosario
790 Formation, Baja California, Mexico. *Marine and Petroleum Geology*, 24, 540-563.
791 <https://doi.org/10.1016/j.marpetgeo.2007.01.003>.
- 792 Kane, I.A. and Hodgson, D.M. (2011). Sedimentological criteria to differentiate submarine channel
793 levee subenvironments: Exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja
794 California, Mexico, and the Fort Brown Fm. (Permian), Karoo Basin, S. Africa. *Marine and*
795 *Petroleum Geology*, 28, 807-823. <https://doi.org/10.1016/j.marpetgeo.2010.05.009>.
- 796 Kane, I.A. and Pontén, A.S.M. (2012). Submarine transitional flow deposits in the Paleogene Gulf
797 of Mexico. *Geology*, 40, 1119-1122. <https://doi.org/10.1130/G33410.1>.
- 798 Kane, I.A., Pontén, A.S.M., Vangdal, B., Eggenhuisen, J.T., Hodgson, D.M. and Spychala, Y.T. (2017).
799 The stratigraphic record and processes of turbidity current transformation across deep-marine
800 lobes. *Sedimentology*, 64, 1236-1273. <https://doi.org/10.1111/sed.12346>.
- 801 Karamitopoulos, P., Weltje, G.J. and Dalman, R.A.F. (2014). Allogenic controls on autogenic
802 variability in fluvio-deltaic systems: inferences from analysis of synthetic stratigraphy. *Basin*
803 *Research*, 26, 767-779. <https://doi.org/10.1111/bre.12065>.
- 804 King, R.C., Hodgson, D.M., Flint, S.S., Graham, J.P. van Lente B. (2009). Development of
805 subaqueous fold belts as a control on the timing and distribution of deepwater sedimentation:

806 an example from the southwest Karoo Basin, South Africa. In Kneller, B., Martinsen, O. J., and
807 McCaffrey, B. (eds.), *External Controls on Deep-Water Depositional Systems. SEPM Special*
808 *Publications*, 92, 261–278. <https://doi.org/10.2110/sepmssp.092.261>.

809 Kneller, B. and McCaffrey, W. (1999). Depositional effects of flow nonuniformity and stratification
810 within turbidity currents approaching a bounding slope: deflection, reflection, and facies
811 variation. *Journal of Sedimentary Research*, 69, 980-991. <https://doi.org/10.2110/jsr.69.980>.

812 Kneller, B. (2003). The influence of flow parameters on turbidite slope channel architecture.
813 *Marine and Petroleum Geology*, 20, 901-910.
814 <https://doi.org/10.1016/j.marpetgeo.2003.03.001>

815 Kneller, B., Bozetti, G., Callow, R., Dykstra, M., Hansen, L., Kane, I. et al. (2020). Architecture,
816 Process, and environmental diversity in a Late Cretaceous slope channel system. *Journal of*
817 *Sedimentary Research*, 90, 1-26. <https://doi.org/10.2110/jsr.2020.1>.

818 Knudson, K.P. and Hendy, I.L. (2009). Climatic influences on sediment deposition and turbidite
819 frequency in the Nitinat Fan, British Columbia. *Marine Geology*, 262, 29-38.
820 <https://doi.org/10.1016/j.margeo.2009.03.002>.

821 Lang, J., Brandes, C. and Winsemann, J. (2017). Erosion and deposition by supercritical density
822 flows during channel avulsion and backfilling: Field examples from coarse-grained deepwater
823 channel-levée complexes (Sandino Forearc Basin, southern Central America). *Sedimentary*
824 *Geology*, 349, 79-102. <https://doi.org/10.1016/j.sedgeo.2017.01.002>.

825 Li, Q., Yu, L. and Straub, K.M., 2016. Storage thresholds for relative sea-level signals in the
826 stratigraphic record. *Geology*, 44(3), 179-182. <https://doi.org/10.1130/G37484.1>.

827 Macdonald, H.A., Peakall, J., Wignall, P.B. and Best, J. (2011). Sedimentation in deep-sea lobe-
828 elements: implications for the origin of thickening-upward sequences. *Journal of the Geological*
829 *Society, London*. 168, 319-331. <https://doi.org/10.1144/0016-76492010-036>.

830 Maslin, M., Knutz, P. C. and Ramsay, T. (2006). Millennial-scale sea-level control on avulsion events
831 on the Amazon Fan. *Quaternary Science Reviews*, 25(23-24), 3338-3345.
832 <https://doi.org/10.1016/j.quascirev.2006.10.012>. Middleton, G.V and Southard, J.B. (1984).
833 *Mechanics of Sediment Movement*. SEPM, Eastern Section Short Course 3 Providence, 401 pp.
834 <https://doi.org/10.2110/scn.84.03>.

835 Mikeš, D., ten Veen, J.H., Postma, G. and Steel, R. (2015). Inferring autogenically induced
836 depositional discontinuities from observations on experimental deltaic shoreline trajectories.
837 *Terra Nova*, 27, 442-448. <https://doi.org/10.1111/ter.12178>.

838 Mohrig, D. and Buttles, J. (2007). Deep turbidity currents in shallow channels. *Geology*, 35, 155-
839 158. <https://doi.org/10.1130/G22716A.1>.

840 Nelson, C.H., Escutia, C., Goldfinger, C., Karabanov, E., Gutierrez-Pastor, J. and De Batist, M. (2009).
841 External controls on modern clastic turbidite systems: three case studies. In Kneller, B.,
842 Martinsen, O.J. and McCaffrey, B. (eds.), *External Controls on Deep-Water Depositional Systems.*
843 *SEPM Special Publications*, 92, 57-76. <https://doi.org/10.2110/sepmssp.092.057>.

844 Normark, W.R. (1970). Growth patterns of deep-sea fans. *AAPG Bulletin*, 54, 2170-2195.
845 <https://doi.org/10.1306/5D25CC79-16C1-11D7-8645000102C1865D>.

- 846 Normark, W.R., Piper, D.J.W. and Sliter, R. (2006). Sea-level and tectonic control of middle to late
847 Pleistocene turbidite systems in Santa Monica Basin, offshore California. *Sedimentology*, 54,
848 867-897. <https://doi.org/10.1111/j.1365-3091.2006.00797.x>.
- 849 Pickering, K.T. (1983). Transitional submarine fan deposits from the late Precambrian Kongsfjord
850 Formation submarine fan, NE Finnmark, N. Norway. *Sedimentology*, 30, 181-199.
851 <https://doi.org/10.1111/j.1365-3091.1983.tb00664.x>.
- 852 Picot, M., Droz, L., Marsset, T., Dennielou, B. and Bez, M. (2016). Controls on turbidite
853 sedimentation: insights from a quantitative approach of submarine channel and lobe
854 architecture (Late Quaternary Congo Fan). *Marine and Petroleum Geology*, 72, 423-446.
855 <https://doi.org/10.1016/j.marpetgeo.2016.02.004>.
- 856 Picot, M., Marsset, T., Droz, L., Dennielou, B., Baudin, F., Hermoso, M., De Rafélis, M., Sionneau,
857 T., Cremer, M., Laurent, D. and Bez, M. (2019). Monsoon control on channel avulsions in the
858 Late Quaternary Congo Fan. *Quaternary Science Reviews*, 204, 149-171.
859 <https://doi.org/10.1016/j.quascirev.2018.11.033>.
- 860 Piper, D. J. W. and Normark, W.R. (1983). Turbidite depositional patterns and flow characteristics,
861 Navy Submarine Fan, California Borderland. *Sedimentology*, 30, 681-694.
862 <https://doi.org/10.1111/j.1365-3091.1983.tb00702.x>.
- 863 Pirmez, C. and Imran, J. (2003). Reconstruction of turbidity currents in Amazon Channel. *Marine
864 and Petroleum Geology*, 20, 823-849. <https://doi.org/10.1016/j.marpetgeo.2003.03.005>.
- 865 Pohl, F., Eggenhuisen, J.T., Tilston, M. and Cartigny, M.J.B. (2019). New flow relaxation mechanism
866 explains scour fields at the end of submarine channels. *Nature Communications*, 10, 4425.
867 <https://doi.org/10.1038/s41467-019-12389-x>.
- 868 Posamentier, H.W. and Kolla, V. (2003). Seismic geomorphology and stratigraphy of depositional
869 elements in deep-water settings. *Journal of Sedimentary Research*, 73, 367-388.
870 <https://doi.org/10.1306/111302730367>.
- 871 Prather, B.E., Pirmez, C., and Winker, C.D., (2012). Stratigraphy of linked intraslope basins: Brazos–
872 Trinity system, western Gulf of Mexico. In Prather, B.E., Deptuck, M.E., Mohrig, D.C., van Hoorn,
873 B., and Wynn, R.B. (eds.), *Application of the Principles of Seismic Geomorphology to Continental-
874 Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues*.
875 *SEPM Special Publications*, 99, 83–109.
876 <https://doi.org/10.2204/%20IODP.proc,%20308.101.2006>
- 877 Prélat, A., Hodgson, D.M. and Flint, S.S. (2009). Evolution, architecture and hierarchy of
878 distributary deep-water deposits: a high-resolution outcrop investigation from the Permian
879 Karoo Basin, South Africa. *Sedimentology*, 56, 2132-2154. <https://doi.org/10.1111/j.1365-3091.2009.01073.x>.
- 881 Prélat, A., Covault, J.A., Hodgson, D.M., Fildani, A., Flint, S.S. (2010). Intrinsic controls on the range
882 of volumes, morphologies, and dimensions of submarine lobes. *Sedimentary Geology*, 232, 66-
883 76. <https://doi.org/10.1016/j.sedgeo.2010.09.010>.
- 884 Rabouille, C., Dennielou, B., Baudin, F., Raimonet, M., Droz, L., Khripounoff, A., Martinez, P.,
885 Mejanelle, L., Michalopoulos, P., Pastor, L. and Pruski, A. (2019). Carbon and silica megasink in
886 deep-sea sediments of the Congo terminal lobes. *Quaternary Science Reviews*, 222, 105854.
887 <https://doi.org/10.1016/j.quascirev.2019.07.036>.

- 888 Romans, B.W., Normark, W.R., McGann, M.M., Covault, J.A., and Graham, S.A. (2009). Coarse-
889 grained sediment delivery and distribution in the Holocene Santa Monica Basin, California:
890 Implications for evaluating source-to-sink flux at millennial time scales. *GSA Bulletin*, 121, 1394–
891 1408. <https://doi.org/10.1130/B26393.1>.
- 892 Romans, B.W., Castelltort, S., Covault, J.A., Fildani, A. and Walsh, J.P. (2016). Environmental signal
893 propagation in sedimentary systems across time-scales. *Earth-Science Reviews*, 153, 7-29.
894 <https://doi.org/10.1016/j.earscirev.2015.07.012>.
- 895 Rouse, H. (1939). Experiments on the mechanics of sediment suspension. In *Proceedings of the*
896 *5th International Congress for Applied Mechanics*, John Wiley, New York, 550–554.
- 897 Shields, A. (1936). Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die
898 Geschiebebewegung. Preussischen Versuchsanstalt für Wasserbau.
- 899 Shumaker, L.E., Jobe, Z.R., Johnstone, S.A., Pettinga, L.A., Cai, D., and Moody, J.D. (2018). Controls
900 on submarine channel-modifying processes identified through morphometric scaling
901 relationships. *Geosphere*, 14, 1–17. <https://doi.org/10.1130/GES01674.1>
- 902 Sømme, T.O., Helland-Hansen, W., Martinsen, O.J. and Thurmond, J.B. (2009). Relationship
903 between morphological and sedimentological parameters in source-to-sink systems: a basis for
904 predicting semi-quantitative characteristics in subsurface systems. *Basin Research*, 21, 361–
905 387. <https://doi.org/10.1111/j.1365-2117.2009.00397.x>.
- 906 Spsychala, Y.T., Hodgson, D.M., Prélat, A., Kane, I.A., Flint, S.S. and Mountney, N.P. (2017). Frontal
907 and lateral submarine lobe fringes: Comparing sedimentary facies, architecture and flow
908 processes. *Journal of Sedimentary Research*, 87, 75-95. <https://doi.org/10.2110/jsr.2017.2>.
- 909 Spsychala, Y.T., Eggenhuisen, J.T., Tilston, M. and Pohl, F. (2019). The influence of basin settings
910 and flow properties on the dimensions of submarine lobe elements. Preprint at
911 <https://eartharxiv.org/sk8v3/>.
- 912 Straub, K.M., Paola, C., Mohrig, D., Wolinsky, M.A. and George, T. (2009). Compensational stacking
913 of channelized sedimentary deposits. *Journal of Sedimentary Research*, 79, 673-688.
914 <https://doi.org/10.2110/jsr.2009.070>.
- 915 Straub, K.M., Pyles, D.R. (2012). Quantifying the hierarchical organization of compensation in
916 submarine fans using surface statistics. *Journal of Sedimentary Research*, 82, 889-898.
917 <https://doi.org/10.2110/jsr.2012.73>.
- 918 Talling, P.J., Wynn, R.B., Masson, D.G., Frenz, M., Cronin, B.T., Schiebel, R. et al. (2007). Onset of
919 submarine debris flow deposition far from original giant landslide. *Nature* 450, 541–544.
920 <https://doi.org/10.1038/nature06313>.
- 921 Toby, S.C., Duller, R.A., De Angelis, S. and Straub, K.M. (2019). A stratigraphic framework for the
922 preservation and shredding of environmental signals. *Geophysical Research Letters*, 46.
923 <https://doi.org/10.1029/2019GL082555>.
- 924 van Rijn, L.C. (1993). Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas (Aqua
925 Publications).
- 926 Wang, Y., Straub, K.M. and Hajek, E.A. (2011). Scale-dependent compensational stacking: An
927 estimate of autogenic time scales in channelized sedimentary deposits. *Geology*, 39, 811-814.
928 <https://doi.org/10.1130/G32068.1>.

- 929 Xu, J.P., Sequeiros, O.E. and Noble, M.A. (2014). Sediment concentrations, flow conditions, and
 930 downstream evolution of two turbidity currents, Monterey Canyon, USA. *Deep Sea Research*
 931 *Part I: Oceanographic Research Papers*, 89, 11-34. <https://doi.org/10.1016/j.dsr.2014.04.001>.
- 932 Yang, W., Kominz, M.A. and Major, R.P. (1998). Distinguishing the roles of autogenic versus
 933 allogenic processes in cyclic sedimentation, Cisco Group (Virgilian and Wolfcampian) north-
 934 central Texas. *GSA Bulletin*, 110, 1333-1353. [https://doi.org/10.1130/0016-7606\(1998\)110%3C1333:DTROAV%3E2.3.CO;2](https://doi.org/10.1130/0016-7606(1998)110%3C1333:DTROAV%3E2.3.CO;2).

936 **SUPPORTING INFORMATION**

937 **Entangled external and internal controls on submarine fan evolution:**
 938 **an experimental perspective**

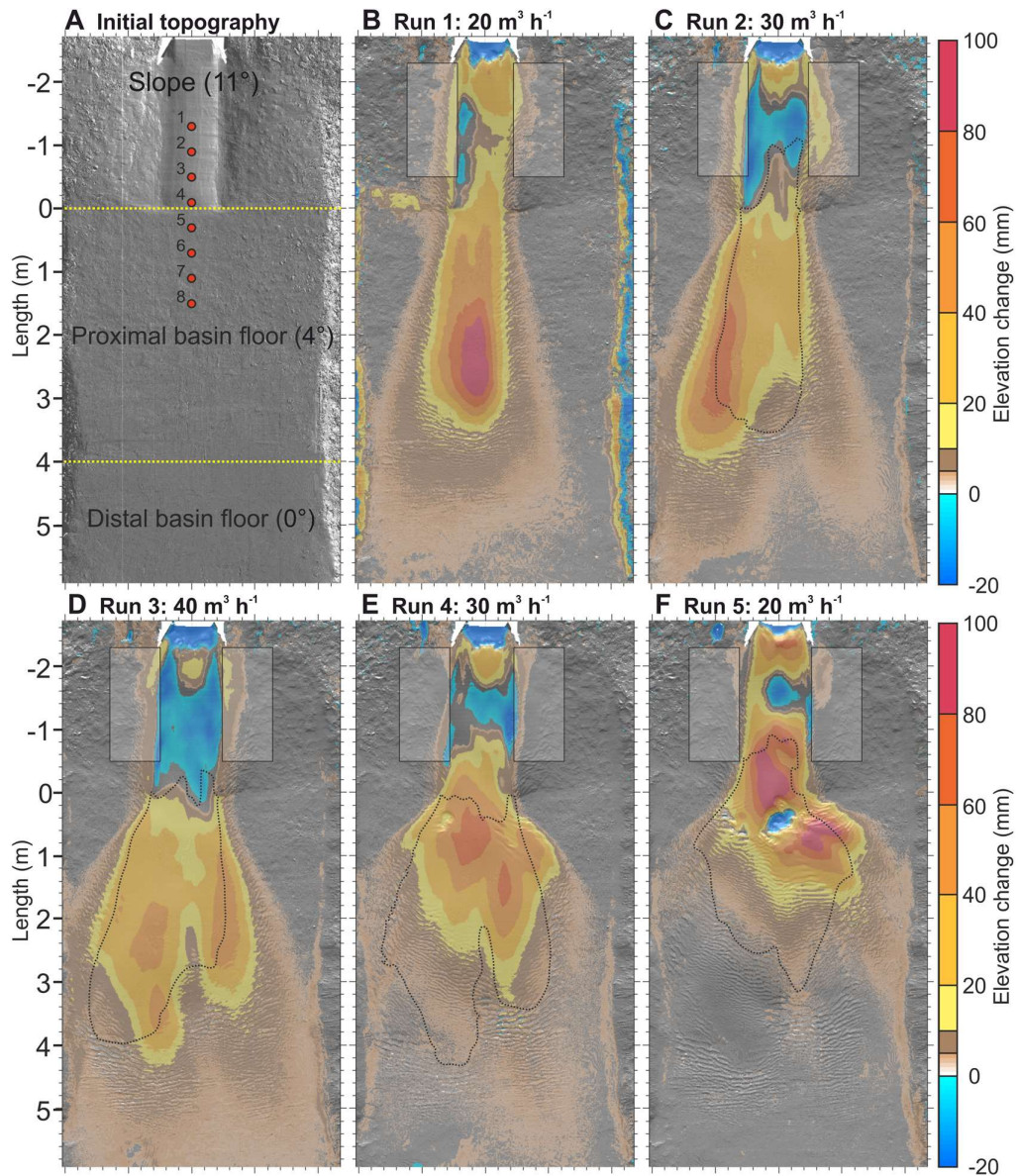
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 940 Brunt¹

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- 944 **SUPPORTING FIGURE 1** Maps of deposition and erosion for each individual run.
- 945 **SUPPORTING FIGURE 2** Digital elevation models of topography before and after a flow with a
 946 sediment supply rate of 10 m³ h⁻¹.
- 947 **SUPPORTING FIGURE 3** Erosion/deposition maps for a separate series of two runs with sediment
 948 supply rates of 20 m³ h⁻¹ and 50 m³ h⁻¹.
- 949 **SUPPORTING FIGURE 4** UVP velocity over time for run 1.
- 950 **SUPPORTING FIGURE 5** UVP velocity over time for run 2.
- 951 **SUPPORTING FIGURE 6** UVP velocity over time for run 3.
- 952 **SUPPORTING FIGURE 7** UVP velocity over time for run 4.
- 953 **SUPPORTING FIGURE 8** UVP velocity over time for run 5.
- 954 **SUPPORTING FIGURE 9** Shield's mobility diagram.
- 955 **SUPPORTING FIGURE 10** Drained flume tank.
- 956 **SUPPORTING TABLE 1** Dynamic and sedimentary properties of experimental flows for all runs at
 957 UVP probes 2 (channel axis) and 8 (proximal basin floor).

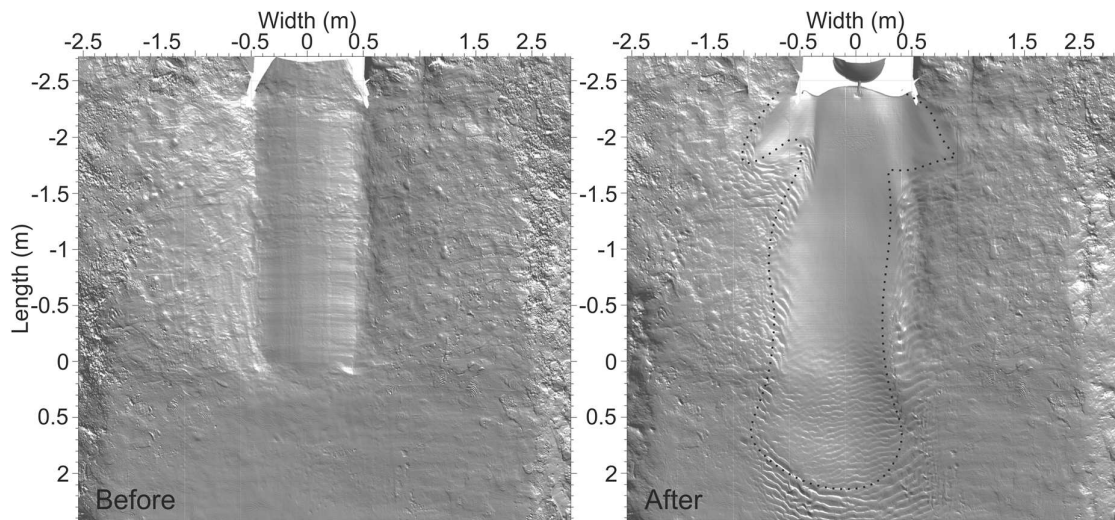


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SUPPORTING FIGURE 1 Maps of deposition and erosion for each individual run. (A) Initial topography. Dotted yellow lines indicate breaks in slope and red dots indicate UVP probe positions. (B) Run 1 ($20 \text{ m}^3 \text{ h}^{-1}$). Notable deposition within channel on the slope. The basin floor deposit was centrally located. Semi-transparent rectangles indicate area used in levee volume calculations (Figure 6). (C) Run 2 ($30 \text{ m}^3 \text{ h}^{-1}$). Increased erosion and overbank deposition on the slope. Flow deflected to the right causing lateral deposition that extended farther into the basin. Dotted black line outlines the main deposit ($> 10 \text{ mm}$) of the previous run. (D) Run 3 ($40 \text{ m}^3 \text{ h}^{-1}$). Maximum sediment supply rate with greatest amount of erosion on the slope. Sediment deposition on the basin floor was widely distributed, favouring topographic lows between previous deposits and extended farther still into the basin. (E) Run 4 ($30 \text{ m}^3 \text{ h}^{-1}$). Decreased erosion and overbank deposition on the slope. The basin floor deposit began to back-step and onlap the slope. (F) Run 5 ($20 \text{ m}^3 \text{ h}^{-1}$). Continuation of back-stepping trend of the deposit led to the channel being substantially infilled. A syn-depositional pocket of apparent erosion caused the deposit to collapse just beyond the break of slope, leading to deflection of the flow and lateral deposition to the left.

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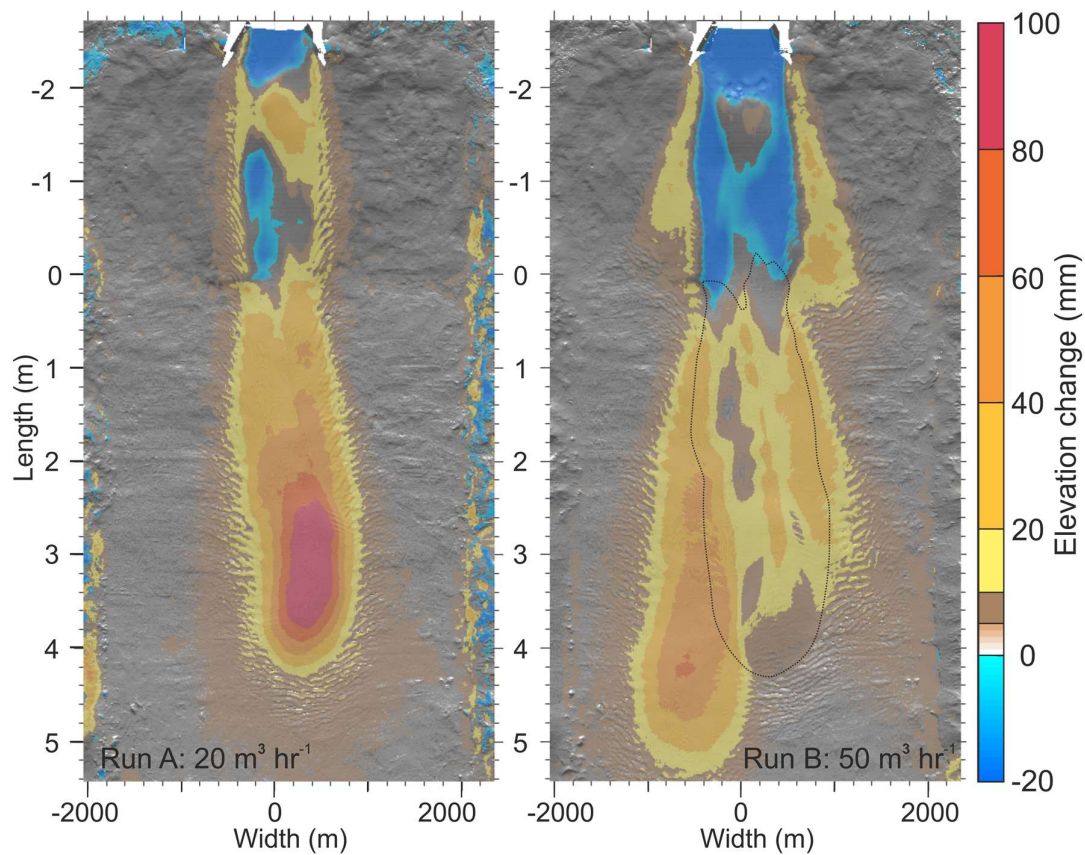
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SUPPORTING FIGURE 2 Digital elevation models of topography before and after a flow with a sediment supply rate of $10 \text{ m}^3 \text{ h}^{-1}$. The flow was highly depositional, and the channel form was completely infilled. Dotted black line in 'after' image indicates approximate depositional area.



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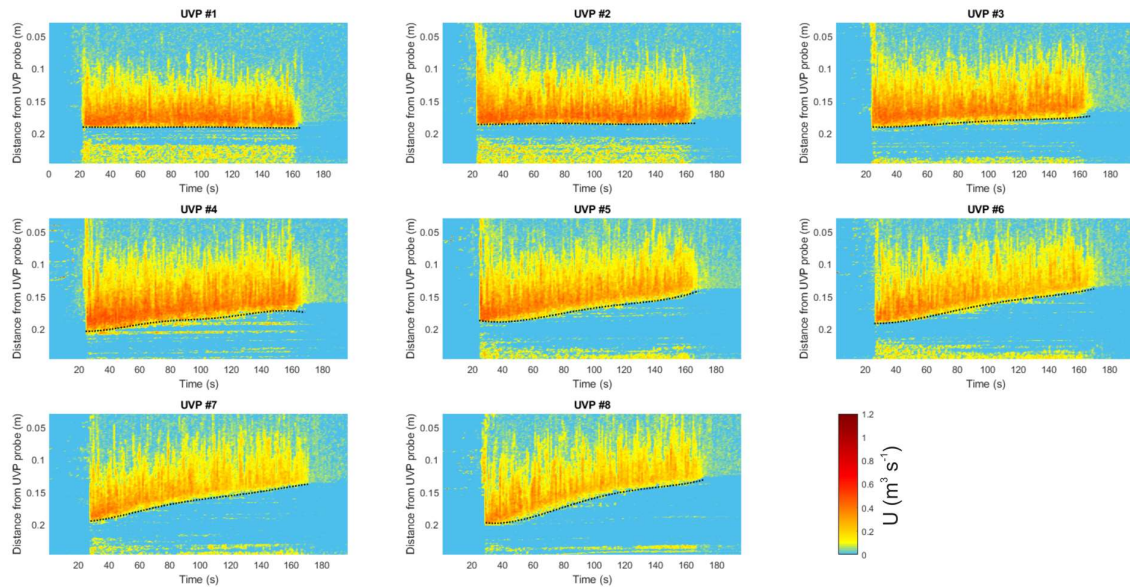
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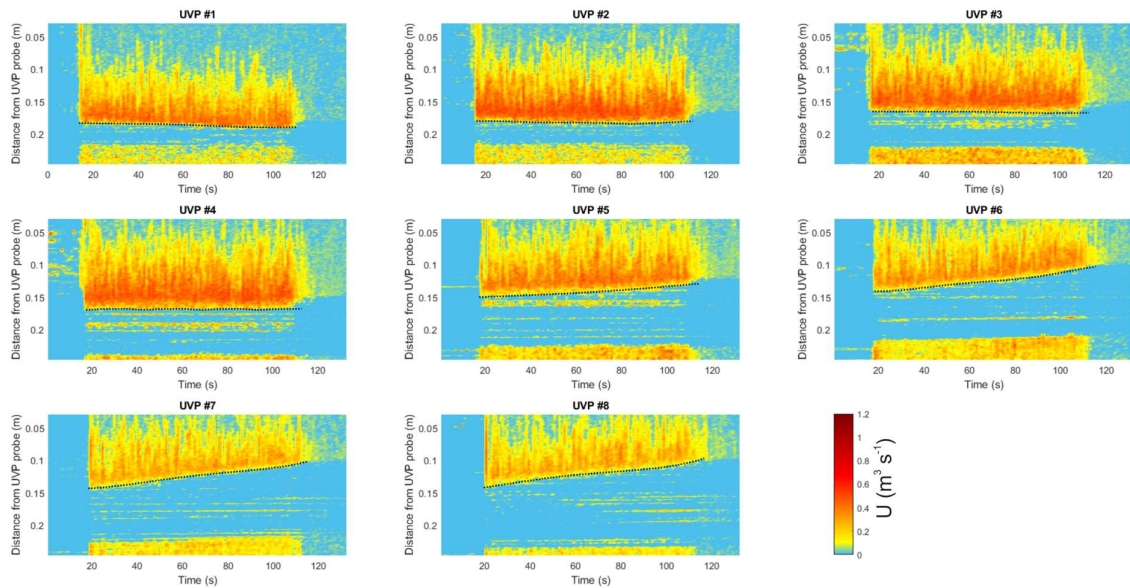
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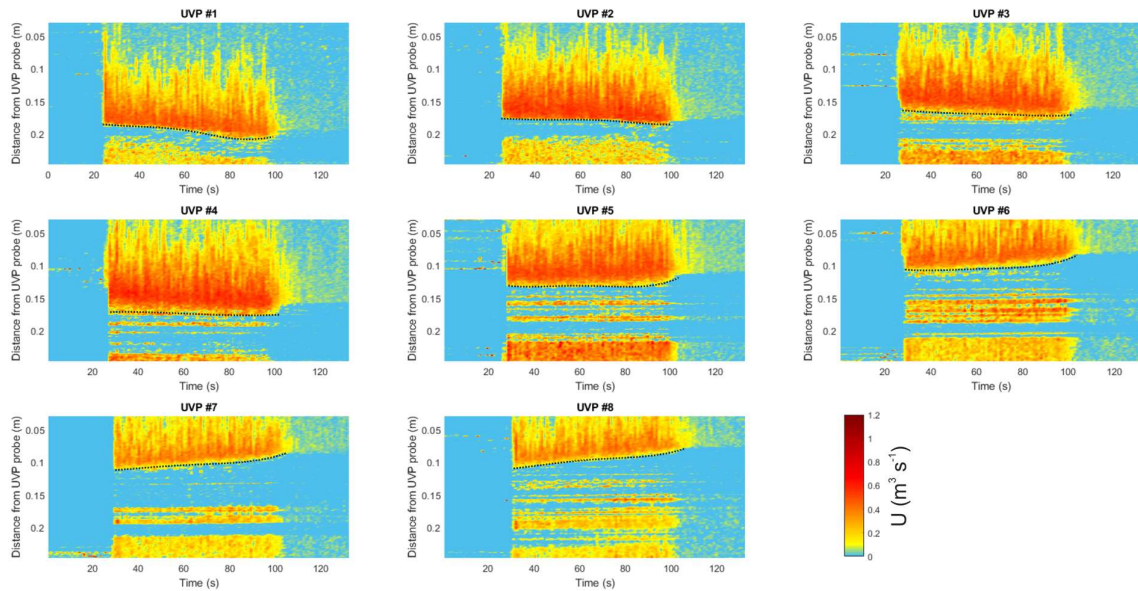
SUPPORTING FIGURE 3 Erosion/deposition maps for a separate series of two runs with sediment supply rates of $20 \text{ m}^3 \text{ h}^{-1}$ and $50 \text{ m}^3 \text{ h}^{-1}$. Run B deposited on top of run A. Excessive channel erosion and deposit runout distance at $50 \text{ m}^3 \text{ h}^{-1}$ led to a maximum sediment supply rate of $40 \text{ m}^3 \text{ h}^{-1}$ being used in the main set of experiments. Black dotted line in run B shows the outline of the deposit from run A.



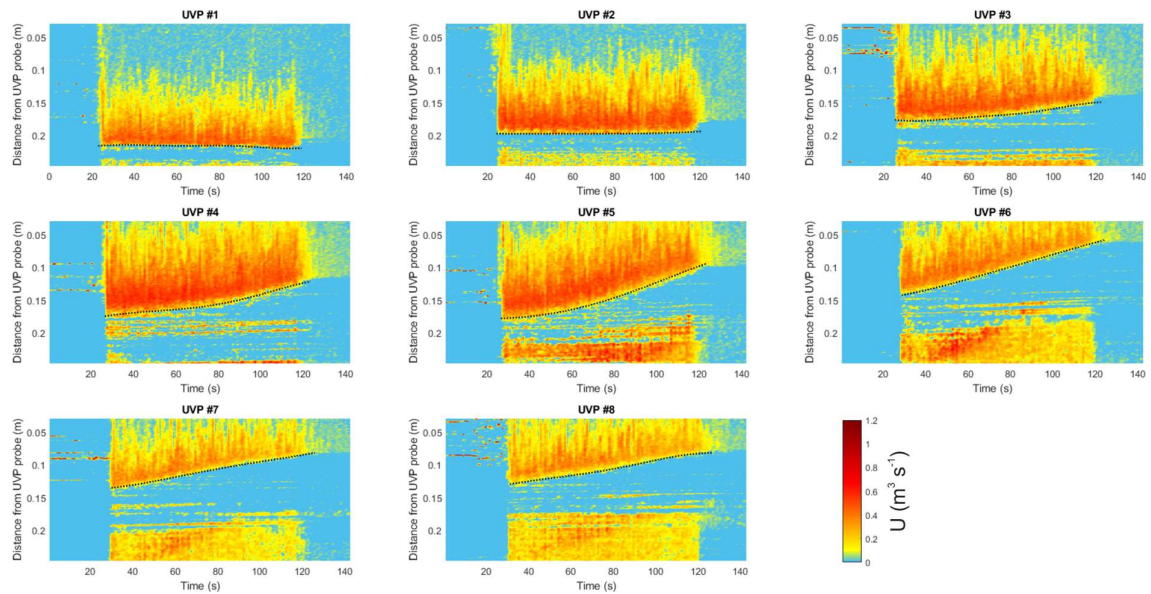
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 984 **SUPPORTING FIGURE 4** UVP velocity over time for run 1. The dotted black line on each profile
 985 indicates interpreted bed base. A rise of the bed base through time indicates progressive deposition
 986 whilst a lowering is indicative of erosion. See Figure 3A for probe locations.



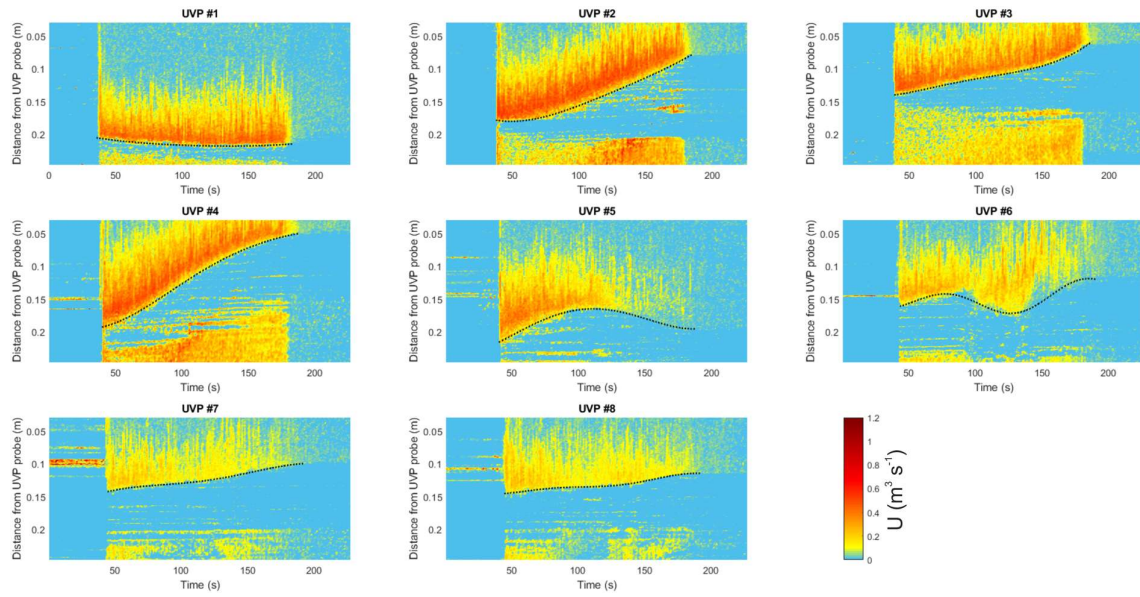
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 988 **SUPPORTING FIGURE 5** UVP velocity over time for run 2. The dotted black line on each profile
 989 indicates interpreted bed base. A rise of the bed base through time indicates progressive deposition
 990 whilst a lowering is indicative of erosion. See Figure 3A for probe locations.



991
 992 **SUPPORTING FIGURE 6** UVP velocity over time for run 3. The dotted black line on each profile
 993 indicates interpreted bed base. A rise of the bed base through time indicates progressive deposition
 994 whilst a lowering is indicative of erosion. See Figure 3A for probe locations.

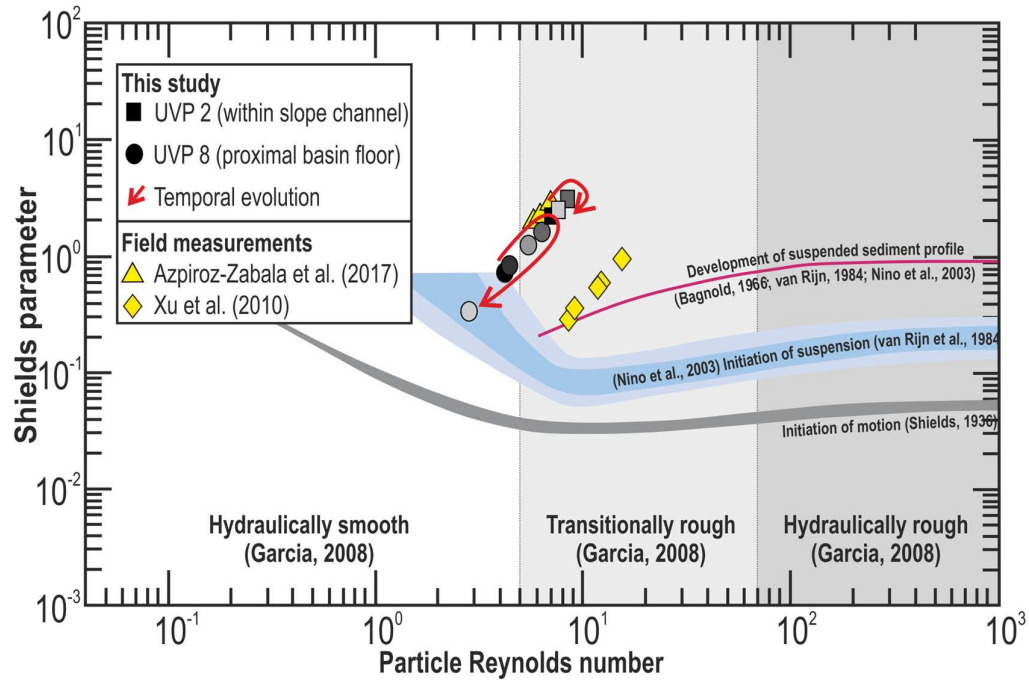


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 996 **SUPPORTING FIGURE 7** UVP velocity over time for run 4. The dotted black line on each profile
 997 indicates interpreted bed base. A rise of the bed base through time indicates progressive deposition
 998 whilst a lowering is indicative of erosion. See Figure 3A for probe locations.



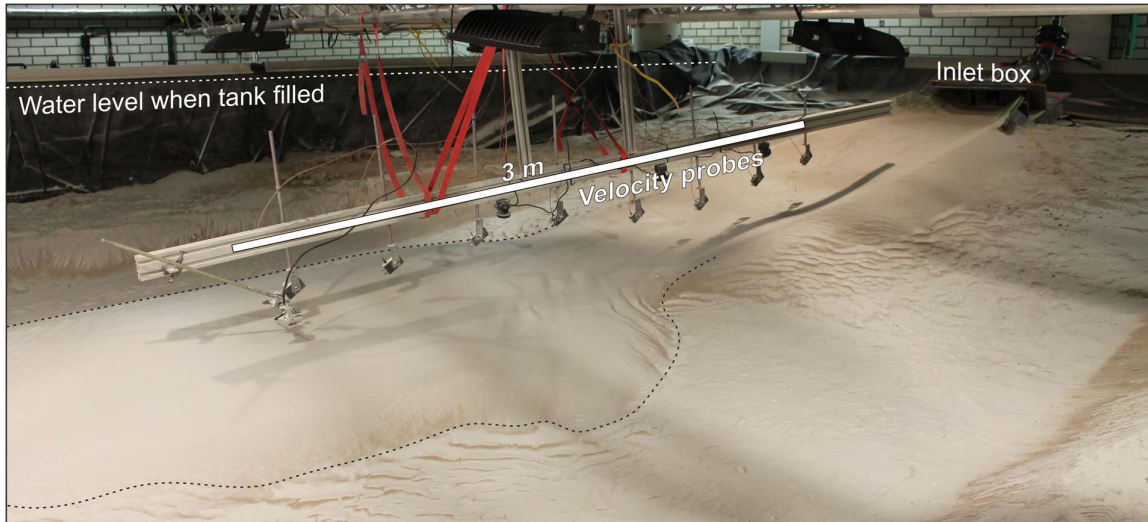
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SUPPORTING FIGURE 8 UVP velocity over time for run 5. The dotted black line on each profile indicates interpreted bed base. A rise of the bed base through time indicates progressive deposition whilst a lowering is indicative of erosion. See Figure 3A for probe locations.



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1004 **SUPPORTING FIGURE 9** Shield's mobility diagram. The present study is plotted within the
 1005 sedimentary transport regime and compared to field studies from the Congo Canyon (Azpiroz-Zabala
 1006 et al., 2017) and the Monterey Canyon (Xu et al., 2010). Modified from (Shields, 1936; de Leeuw et al.,
 1007 2016; Fernandes et al., 2018). The slope channel (UVP 2) plots within the transitionally rough regime
 1008 and above the threshold for development of a suspended sediment profile in all five runs. The
 1009 proximal basin floor (UVP 8) results span the hydraulically smooth to transitionally rough regimes and
 1010 drop to the 'initiation of suspension' zone in run 5. Colours from dark to light represent runs 1 through
 1011 5 respectively and arrows indicate the general temporal evolution for clarity. Note that values rise and
 1012 fall in line with the increasing to decreasing sediment supply rates. Regime boundaries after: (Shields,
 1013 1936; van Rijn, 1984; Garcia, 2008; Bagnold, 1966; Nino et al., 2003).



1014

1015 **SUPPORTING FIGURE 10** Drained flume tank. Image shows the drained tank with the deposits of
1016 runs 1–4 prior to running the final experiment. Dotted black line indicates the approximate area of the
1017 composite deposit.

1018 **SUPPORTING TABLE 1** Dynamic and sedimentary properties of experimental flows for all runs at
 1019 UVP probes 2 (channel axis) and 8 (proximal basin floor). See Figure 2 for probe locations.

Run No.	Run 1		Run 2		Run 3		Run 4		Run 5	
UVP No.	2	8	2	8	2	8	2	8	2	8
U_{max} (maximum velocity, $m\ s^{-1}$)	0.820	0.524	0.948	0.535	1.093	0.762	0.991	0.639	0.971	0.328
h_{max} (height of U_{max} , m)	0.010	0.016	0.014	0.012	0.020	0.012	0.016	0.010	0.016	0.010
ρ_a (ambient fluid density $kg\ m^{-3}$)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
ρ_s (sediment density, $kg\ m^{-3}$)	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650
ρ_f (current density, $kg\ m^{-3}$)	1280.5	1280.5	1280.5	1280.5	1280.5	1280.5	1280.5	1280.5	1280.5	1280.5
Conc. Vol. of sediment in suspension	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
D_{90} (m)	2.23E-04	2.23E-04	2.23E-04	2.23E-04	2.23E-04	2.23E-04	2.23E-04	2.23E-04	2.23E-04	2.23E-04
D_{50} (m)	1.31E-04	1.31E-04	1.31E-04	1.31E-04	1.31E-04	1.31E-04	1.31E-04	1.31E-04	1.31E-04	1.31E-04
D_{10} (m)	2.50E-05	2.50E-05	2.50E-05	2.50E-05	2.50E-05	2.50E-05	2.50E-05	2.50E-05	2.50E-05	2.50E-05
k (Karman's Constant)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
g (gravitational acceleration, $m\ s^{-1}$)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
ν (kinematic viscosity)	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
U^* (shear velocity, m/s)	0.0537	0.0320	0.0588	0.0342	0.0645	0.0487	0.0601	0.0419	0.0588	0.0214
Re_p (particle Reynolds No.)	7.037	4.192	7.706	4.480	8.455	6.379	7.878	5.486	7.704	2.810
τ^* (Shields parameter)	2.100	0.745	2.517	0.851	3.031	1.725	2.631	1.276	2.516	0.335

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1021 **SUPPORTING REFERENCES**

- 1022 Azpiroz-Zabala, M., Cartigny, M.J.B., Sumner, E.J., Clare, M.A., Talling, P.J., Parsons, D.R. and
1023 Cooper, C. (2017). A general model for the helical structure of geophysical flows in channel
1024 bends. *Geophysical Research Letters*, 44, 11,932–11,941.
1025 <https://doi.org/10.1002/2017GL075721>.
- 1026 Bagnold, R.A. (1966). An approach to the sediment transport problem from general physics.
1027 *Geological Survey Professional Paper*, Washington DC, 442-I, 1-37.
- 1028 de Leeuw, J., Eggenhuisen, J.T. and Cartigny, M.J.B. (2016). Morphodynamics of submarine
1029 channel inception revealed by new experimental approach. *Nature Communications*, 7, 10886.
1030 <https://doi.org/10.1038/ncomms10886>.
- 1031 Fernandes, A.M., Buttles, J. and Mohrig, D. (2018). Flow-Substrate Interactions in Aggrading and
1032 Degrading Submarine Channels. Preprint at <https://eartharxiv.org/ceyhk/>.
1033 <https://doi.org/10.31223/osf.io/ceyhk>.
- 1034 Garcia, M. (2008). Sedimentation Engineering: Processes, Measurements, Modeling and Practice.
1035 *American Society of Civil Engineering*, 1132 pp. <https://doi.org/10.1061/9780784408148>
- 1036 Nino, Y., Lopez, F. and Garcia, M. (2003). Threshold for particle entrainment into suspension.
1037 *Sedimentology*, 50, 247–263. <https://doi.org/10.1046/j.1365-3091.2003.00551.x>.
- 1038 Shields, A. (1936). Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die
1039 Geschiebebewegung (Preussischen Versuchsanstalt für Wasserbau).
- 1040 Van Rijn, L. C. (1984). Sediment transport, part II: suspended load transport. *Journal of Hydraulic*
1041 *Engineering*, 110, 1613-1641.
- 1042 Xu, J. P. (2010). Normalized velocity profiles of field-measured turbidity currents. *Geology* 38, 563–
1043 566. <https://doi.org/10.1130/G30582.1>