

1 **Flow-Substrate Interactions in Aggrading and Degrading Submarine Channels**

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7 separation zones; erosional bedforms; detachment-limited channels; transport-limited channels; Shields
8 scaling

9 **ABSTRACT**

10 Connecting real time measurements of current-bed interactions to the temporal evolution of
11 submarine channels can be extremely challenging in natural settings. We present a suite of physical
12 experiments that offer insight into the spectrum of interactions between turbidity currents and their
13 channels, from (i) detachment-limited erosion to (ii) transport-limited erosion to (iii) pure deposition. In
14 all three cases channel sinuosity influenced patterns of erosion and deposition; the outsides of bends
15 displayed the highest erosion rates in the first two cases, whereas the outsides of bends were associated
16 with the highest deposition rates the third. We connect the evolution of these channels to the turbulence of
17 the near-bed boundary layer. In the erosional experiments both channel beds roughened through time,
18 developing erosional bedforms or trains of ripples. Reynolds estimates of boundary layer roughness
19 indicate that, in both erosional cases, the near-bed boundary layer roughened from smooth or
20 transitionally rough to rough, whereas the depositional channel appears to have remained consistently
21 smooth. Our results suggest that, in the absence of any changes from upstream, erosion in submarine
22 channels is a self-reinforcing mechanism whereby developing bed roughness increases turbulence at the
23 boundary layer, thereby inhibiting deposition, promoting sediment entrainment and enhancing channel

24 relief; deposition occurs in submarine channels when the boundary layer remains smooth, promoting
25 aggradation and loss of channel relief.

26 **INTRODUCTION**

27 Continental margins are patterned with channels and canyons that convey large volumes of
28 sediment to the deep ocean. These channels evolve through erosion and/or deposition, often aggrading
29 over significant vertical distances (Pirmez et al., 2000), or by carving canyons (Babonneau et al., 2010;
30 Conway et al., 2012) many hundreds of meters deep. Physical experiments can offer insight into current-
31 bed interactions. Such measurements are challenging to acquire in natural settings and even more
32 challenging to relate to the temporal evolution of submarine channels (Khripounoff et al., 2003; Xu et al.,
33 2004, 2013; Xu, 2010; Hughes Clarke, 2016; Symons et al., 2017; Azpiroz-Zabala et al., 2017b, 2017a).
34 In the past, some experiments e.g. (Mohrig and Buttle, 2007; Straub et al., 2008; Janocko et al., 2013)
35 focused on purely depositional turbidity currents that were suspension-dominated, whereas others
36 investigated erosional currents that modified channels primarily through bedload-transport (Métivier et
37 al., 2005; Amos et al., 2010). Here we present three experiments which we use to explore the processes
38 that shape submarine channels, along the continuum of intensely erosional to purely depositional in
39 connection to the hydraulic characteristics of the near-bed boundary layer, across this spectrum of
40 behavior.

41 **Detachment-limited and transport-limited erosion in terrestrial landscapes**

42 Terrestrial channels eroding into bedrock have been modeled using: a) a detachment-limited model
43 in which the resistance of the substrate is the limiting factor that controls the erosion rate, and b) a transport-
44 limited model where the erosion rate is limited by the ability to transport the eroded sediment (Howard,
45 1980, 1994; Whipple, 2004). Detachment-limited erosion is more sensitive to local conditions (e.g.
46 topographic or bed roughness) rather than reach-averaged conditions (e.g. discharge; (Johnson and
47 Whipple, 2007)). Erosion generally takes place through abrasion and wear by the impacts of sediment being
48 transported by the flow, and turbulence generated by evolving bed roughness. These channels are

49 characterized by knickpoints, inner channels, scour holes, grooves, and sculpted bedforms (Whipple, 2004).
50 The transporting currents are efficient at removing sediment in transport from upstream and at entraining
51 material from the local substrate.

52 When the removal of eroded sediment is not efficient, sediment is stored in patches on the bed,
53 protecting the bed from further erosion in a phenomenon referred to as the ‘cover-effect’ (Johnson et al.,
54 2009). Erosional channels with abundant sediment cover on the channel bed are referred to as “transport-
55 limited” (Shepherd and Schumm, 1974; Sklar and Dietrich, 2004; Whipple, 2004; Johnson and Whipple,
56 2007). Partially-alluviated erosional channels scouring into compact, indurated sediment have been
57 observed in depositional landscapes such as the Mississippi River Delta (Edmonds et al., 2011; Nittrouer
58 et al., 2011a), where cover effects are particularly evident. Channel bottoms display deep scours where they
59 are devoid of alluvial cover at the outsides of river bends. All natural erosional channels can be expected to
60 display some combination of detachment-limited and transport-limited behavior (Whipple, 2004). Here we
61 use 2 experiments to study the characteristics of detachment-limited and transport-limited erosion in
62 submarine channels. For completeness, we incorporate data from an aggradational channel experiment
63 (Straub et al., 2008). We use these experiments to explore the role of the near-bed boundary layer in the
64 spectrum of forms and deposit characteristics observed.

65 **Dynamic scaling of experiments to natural systems**

66 Laboratory experiments have historically been compared to natural systems by using three
67 dimensionless variables: (1) the densimetric Froude number (Fr_d), (2) the Reynolds number (Re), and (3)
68 the ratio of current shear velocity u^* to particle fall velocity w_s (Middleton, 1966; Baas et al., 2004; Yu et
69 al., 2006; Mohrig and Buttle, 2007; Straub et al., 2008; Amos et al., 2010; Rowland et al., 2010; Cantelli
70 et al., 2011). The first parameter, the Froude number, defines the ratio between momentum and
71 gravitational forces within the transporting current and is traditionally maintained equal or similar to
72 natural analogues. The Reynolds number, which quantifies the turbulence of the currents, cannot be equal
73 to natural flows in scaled-down laboratory settings. The third parameter, also referred to as a Shield’s

74 parameter (Shields, 1936; Bagnold, 1966; Smith and Hopkins, 1971; van Rijn Leo C., 1984; Nino et al.,
75 2003), characterizes how sediment is transported. Flows in which the turbulent shear, expressed as the
76 shear velocity u^* , is significantly larger than the gravitational settling velocity w_s will be more competent
77 at transporting sediment in suspension over significant distances (Shields, 1936; Smith and Hopkins,
78 1971) and will preclude sediment-bed interactions over short length scales; if u^* is comparable to w_s ,
79 sediment can be transported as either saltating or incipiently suspended load, dependent upon the intensity
80 of turbulence associated with current-bed interactions. In channelized turbidity currents, the intensity of
81 near-bed turbulence is the combined result of turbulent eddies shed at the scale of individual particles (de
82 Leeuw et al., 2016), of bed roughness (e.g. bedforms, scours, etc.) (Eggenhuisen et al., 2010;
83 Eggenhuisen and McCaffrey, 2012; Arfaie et al., 2018), as well as of planform irregularities (e.g. curved
84 channels) (Straub et al., 2011) which can impart turbulent shear from non-uniform spatial accelerations.
85 The magnitude of turbulence will scale with the magnitudes of fluid shear (u^*) and the size of the element
86 under consideration (e.g. particle diameter, dune height, scour depth, bend amplitude, etc.). Turbulence
87 associated with these roughness scales contributes to entrainment of sediment from the bed and walls of
88 channels, and encourages vertical mixing which maintains sediment in suspension. The ratio between
89 fluid shear and the viscous forces which act to damp turbulence can be used to characterize the roughness
90 of the near-bed boundary layer (Garcia, 2008).

91 De Leeuw et al. (2016) argued that realistic turbulence-sediment interactions were critical for
92 effectively modelling submarine channel inception and evolution, and proposed a scaling approach defined
93 by the ratio of the Shield's parameter to the particle Reynolds number (Re_p). In this scaling approach, the
94 Shield's parameter is held similar between experimental and naturally occurring density currents, but the
95 similarity between the particle Reynolds numbers is relaxed as long as the boundary layer is rough or
96 transitionally rough (Garcia, 2008; de Leeuw et al., 2016). Leeuw et al. (2017) noted that density currents
97 in most previous experiments were highly depositional because the boundary layers were hydraulically
98 smooth and/or the Shields parameter fell below the initiation of suspension.

99 In Figure 1, we adopt the Shield's scaling proposed by de Leeuw et al. (2016) to compare flow and
100 sediment transport characteristics of the three experiments presented here to past experimental and field
101 measurements. Although the shear stresses associated with all three experiments exceeded the threshold for
102 the initiation of suspension, they straddle the threshold between hydraulically smooth and transitionally
103 rough boundary layers. Furthermore, Experiments 1 and 2 scale best with recent field observations of flow
104 and transport in natural systems. Using sediment with much lower densities than silica in these experiments
105 allowed us to use sand-sized particles that had transitionally rough boundary layers and high Shields
106 parameters, and were therefore easy to suspend and maintain in suspension.

107 **Experiment Design**

108 In each experiment, calcium chloride salt and water (and sediment, when it was used), were mixed
109 together in a reservoir, until the salt was completely dissolved. The mixture was agitated over several hours
110 and allowed to cool to room temperature, as the dissolution of this salt in water is an exothermic process.
111 Once at room temperature, the mixture was pumped up to a constant head tank and then allowed to flow
112 into the experimental basin at a controlled rate set by the constant hydraulic head and a system of valves.
113 The two experimental basins were designed along similar lines, shown by the generalized schematic in
114 Figure 2. In all experiments, density currents were released into an experimental channel through a box
115 with two perforated screens designed to extract momentum from flows. The pre-formed channels were built
116 upon a platform separated from the walls of the basin by deep moats that prevented currents from reflecting
117 off the basin walls. Saline fluid was not allowed to collect in the basin and was extracted through the floor
118 drains as it flowed off the raised platform. The water level in the basin was maintained with a constant flux
119 of fresh water and overflow drainage through a weir. The basin used in Experiment 1 was 8 m long, 6 m
120 wide and 2 m deep. The basin used for Experiments 2 & 3 was 5 m long, 4.5 m wide and 0.8 m deep. In all
121 experiments, the channel was constructed diagonally across the false floor.

122 The channels used in these experiments were designed with similar sinuosity, but different
123 sediment and flow properties (Table 1). In Experiment 1, the channel was built entirely out of a weakly
124 cohesive mixture of acrylic particles (specific gravity = 1.15) and clay positioned on top of a sloping ramp.

125 The sediment was mixed in a 10:1 volumetric ratio. The first two currents released into the channel were
 126 saline density currents (excess density = 4%). These were followed by three more density currents that
 127 carried a 2% volumetric concentration of suspended acrylic sediment.

128 In Experiment 2 a saline density current (excess density = 3.32%) was released through the
 129 experimental channel which consisted of a cohesionless, 2-cm thick bed of acrylic particles draped over a
 130 sinuous channel form built from concrete. In Experiment 3 sixteen purely depositional currents flowed
 131 through a channel constructed of concrete with a thin layer of silica sediment on the bed. Currents had an
 132 excess density of 2.1%. 33% of this excess density was supplied by suspended sediment in the current, and
 133 the remaining 67% was from dissolved salt. High-resolution bathymetry maps (horizontal resolution =
 134 4mm; vertical resolution ~100 microns for Experiments 1 & 2; ~1mm for Experiment 3), collected before
 135 and after each flow defined patterns of bed change for all three cases. Key geometric and dynamic properties
 136 of the experimental designs are compiled in Table 1.

137 **Table 1: Summary of geometric and dynamic properties of Experiments 1, 2 and 3.**

	Parameter	Experiment 1	Experiment 2	Experiment 3
Channel geometry	Channel depth (m)	0.15	0.09	0.11
	Channel width (m)	0.50	0.40	0.40
	Down-channel slopes (degrees)	7.00	2.00	1.00
	Initial mean thickness of erodible bed (m)	0.07	0.02	0.00
	Channel sinuosity	1.15	1.28	1.28
Sediment properties	Sediment density (ρ_s) (kg/m ³)	1150.00	1150.00	2650.00
	D ₁	49	49	1.7
	D ₁₀	88	88	12.9
	D ₂₅	127	127	23
	D ₅₀	146	146	31
	D ₇₅	205	205	41
	D ₉₀	243	243	52.1
	D ₉₉	340	340	80
Flow properties	Flow thickness (m)	0.10	0.09	0.10
	Current density (ρ_f) (kg/m ³)	1040	1033.20	1021
	Depth-averaged downstream velocity (u) (m/s)	0.10	0.05	0.08
	Shear velocity (u*) (m/s)	0.04	0.03	0.04
	Froude number (Fr)	0.50	0.26	0.56
	Reynolds number (Re)	10000.00	4050.00	8000.00
	Particle Reynolds number (Re _p)	6.53	4.38	1.24
	Shields parameter	13.20	5.56	3.30
	Bed roughness scale (H _{bed}) (m)	0.01 - 0.05	0.01 - 0.02	-
Reynolds number from bed roughness (Re _{bed})	~650 - 2236	~330- 660	-	

138

139 **Results**

140 Integrating surface change for each flow in all three cases reveal net erosion in Experiments 1 and
141 2, and net deposition in Experiment 3.

142 **Experiment 1**

143 In Experiment 1, all 5 currents released through the channel modified it through net erosion (Fig.
144 3 A, Fig. 4). The weakly cohesive bed consisted of sediment that was easily suspended once it detached
145 from the surface (Fig. 1). Extreme run-up of currents onto the outer walls of channel bends occurred,
146 resulting in the formation of a low-velocity flow-separation zone (depth-averaged velocity \approx 1-2 m/s) at
147 the inner bank (Fig. 4G; Fig.5) (Leeder and Bridges, 1975; Fernandes et al., 2018). Erosion occurred
148 beneath the pathway of the high-velocity (depth-averaged velocity = 10m/s) core of the current, which
149 travelled along the outside of bends and created a series of discontinuous scours. Initially, while the channel
150 bed was smooth, the most intense scouring occurred at the outside of bends (Fig. 4A, B, H; Fig. 6).
151 Subsequently, the rough edges of scours became sites of focused erosion (Fig. 4C-F, I-L; Fig. 6A-C) and
152 resultant elongation of scours resulted in the formation of a discontinuous inner channel (Fig. 7A- B).
153 Focused erosion at the downstream edges of scours released clouds of suspended sediment that were
154 transported downstream and out of the system. Consecutive inner bank areas were separated by a swath of
155 erosion, and evolved into raised terraces within the low-velocity flow separation zone (Fig. 3A, Fig. 4;
156 (Fernandes et al., 2018). The channel bed evolved from smooth to ornamented, displaying erosional
157 bedforms with centimeter-scale relief (Fig. 3A; Fig. 6). These bed morphologies are similar to those
158 observed in detachment-limited terrestrial channels, where erosion is limited by the strength of the substrate
159 and bed erosion occurs primarily through wear by abrasion and plucking (Whipple et al., 2000; Whipple,
160 2004). The channel remained net-erosional through its entire length (Fig. 3A; Fig. 4).

161 **Experiment 2**

162 This channel was modified through net-erosion, with a fraction of mobilized sediment leaving the
163 system in suspension while the remainder was reworked into a continuous train of bedforms (Fig. 3B). As
164 in Experiment 1, the high velocity core of the density current travelled along the outsides of bends, resulting
165 in: 1) erosion of sediment at the outer bank, where sediment removal exposed the underlying erosion-
166 resistant channel form in the troughs between sediment-starved bedforms, and 2) deposition at the inner
167 bank, which resulted from the convergence of downstream and cross-stream bedload transport (Fig. 3B,
168 Fig 7C-D). These zones of deposition began just upstream from the points of maximum channel curvature,
169 and were connected across inflection points through the continuous bedform field (Fig. 4B). Erosion in this
170 experiment was less efficient than in Experiment 1. Abundant sediment cover on the channel bed is
171 suggestive of erosional mechanics similar to that of transport-limited erosional terrestrial channels, which
172 are also characterized by alluviated channel beds interrupted by variable degrees of local scouring
173 (Whipple, 2004; Nittrouer et al., 2011a, 2011b), and in which the erosion rate is limited by the ability of
174 the flow to transport the eroded sediment.

175 **Experiment 3**

176 Currents modified this channel via net sediment deposition (Straub et al., 2008). The thickest
177 deposition closely tracked the pathway of the high velocity core, which was inferred to be the pathway of
178 the highest suspended sediment concentration (Fig. 9 of Straub et al., 2008). This resulted in thicker deposits
179 at the outer banks of bends and thinner deposits in low-velocity zones at the inner banks of bends (Fig. 3C,
180 Fig. 7E-F). Deposits from each current draped the entire channel (Fig. 7E-F), and thinned in the downstream
181 direction (Fig. 6D-F). Sediment was primarily transported as and deposited from suspended load.
182 Suspended sediment flux was estimated to be roughly 40 times that of bedload flux (Straub et al., 2008).

183 **Discussion**

184 **Boundary layer roughness in erosional and depositional channels**

185 The transporting currents in all three experiments had shear stresses that were high enough to
186 transport sediment in suspension. Yet their temporal evolution spanned the spectrum from intense erosion
187 to pure deposition. In all three cases, planform irregularity influenced the spatial variability in sedimentation
188 and/or erosion by influencing the path of the highest velocities and sediment concentrations. A key
189 difference between the 3 experiments lies in the characteristics of the hydraulic boundary layer and the
190 temporal evolution of the three channels suggests strong agreement with the Shield-scaling predictions of
191 de Leeuw et al., 2016. Particle-scale Reynolds estimates of boundary layer turbulence place Experiment 1
192 in the transitionally rough hydraulic regime, whereas Experiment 2 was at the approximate boundary
193 between the smooth and transitionally rough regime, and Experiment 3 was squarely within the
194 hydraulically smooth regime. Furthermore, Experiment 1 evolved from a smooth bed to one patterned by
195 scours, grooves and other centimeter-scale erosional bedforms; Experiment 2 evolved from a smooth bed
196 into a semi continuous bedform field. In both erosional experiments the roughening of the channel bed is
197 likely to have encouraged greater turbulence at the near-bed boundary (Fig. 2).

198 At the start of Experiment 1, the smooth sediment bed was modified by erosion along the pathway
199 of the high velocity core; the magnitude of erosion appeared to be greatest near the outsides of bends (Fig.
200 4A, B, G, H). Particle Reynolds numbers calculated from mean, depth-averaged downstream velocities at
201 the outsides (0.1 m/s) and insides (0.01 - 0.02 m/s) of bends point to a hydraulically smooth boundary layer
202 within the flow separation zone at the inside of the bend, and a transitionally rough boundary layer at the
203 outside (Fig. 2). The emergence of erosional roughness with 1-5 centimeter relief is likely to have further
204 roughened the boundary layer, prohibiting sediment deposition and increasing erosion at sites with
205 enhanced roughness (Fig. 3A; Fig. 4; Fig.6). Near bed turbulence increased by at least two orders of
206 magnitude ($Re_{bed} \sim 450$ for 1cm relief; $Re_{bed} \sim 2200$ for 5cm relief; Fig. 2), causing a regime shift towards
207 a hydraulically rough boundary layer (Garcia, 2008). Hydraulically smooth boundary layers in flow
208 separation zones at the inner banks (Fig. 2) precluded erosion and very low suspended sediment fluxes were
209 unfavorable for deposition. Overall, Experiment 1 evolved in such a way that sediment entrainment and

210 removal remained efficient through time, and channel relief consistently increased as currents scoured into
211 the ~7cm thick erodible sediment bed (Fig. 6A; Fig 7A). Detachment-limited erosion is indicated by
212 evolution of sculpted erosional bedforms, efficient sediment removal and enhanced erosion linked to local
213 bed roughness. The temporal evolution of this channel therefore offers significant insights into the evolution
214 of topography and flow-bed interactions in detachment-limited erosional submarine channels and canyons
215 e.g. (Conway et al., 2012; Vachtman et al., 2013; Mitchell, 2014) that incise into compacted or indurated
216 fine-grained sediment on the upper continental slope and are efficient, dominantly-erosional conduits for
217 sediment transport into the deep ocean.

218 Like Experiment 1, Experiment 2 also evolved from a smooth bed to a rough one and the outer
219 banks of bends were sites of enhanced erosion. Using ripple crest height of 1-2 cm as the relevant length
220 scale, Reynolds estimates indicate that the boundary layer evolved to become hydraulically rough (Fig. 2;
221 (Garcia, 2008), though it was at the threshold between hydraulically smooth and transitionally rough at the
222 start of the experiment (Table 1). The Shields parameter for all particle sizes present falls above the
223 threshold for initiation of suspension (Shields, 1936; Bagnold, 1966; Smith and Hopkins, 1971; van Rijn
224 Leo C., 1984; Nino et al., 2003), suggesting that the rate of erosion was limited by the currents' capacity to
225 transport the sediment in suspension, and that the sediment that could not be suspended was transported as
226 bedload. The development of a bedform field, while it likely facilitated sediment entrainment by roughening
227 the boundary layer probably also reduced fluid momentum and the capacity of the current to suspend
228 sediment. This style of transport-limited erosion (Whipple, 2004; Johnson and Whipple, 2007) likely offers
229 insight into the delicate balance of flow-sediment feed-backs that control spatially variable sedimentation
230 and erosion in dominantly bypassing submarine channels on the middle or lower continental slope.

231 Unlike Experiments 1 and 2, Experiment 3 remained depositional for the duration of the
232 experiment. Straub et al., (2008) noted that super-critically climbing ripples were present over only
233 approximately 5% of the sediment bed. Consistent deposition and reduction in channel relief (Straub et al.,
234 2008) through time suggests that the boundary layer characteristics likely shifted further into the

235 hydraulically smooth regime. We suggest that this style of evolution would be most characteristic of
236 channels near the terminus of submarine transport systems, on terminal lobes on the basin flow where
237 sediment is delivered by depletive flows that are unable to re-entrain sediment.

238 **CONCLUSIONS**

239 It is extremely challenging to connect current-bed interactions to the temporal evolution of
240 submarine channels in natural settings (Khripounoff et al., 2003; Xu et al., 2004, 2013; Xu, 2010; Hughes
241 Clarke, 2016; Symons et al., 2017; Azpiroz-Zabala et al., 2017b, 2017a). We used 3 experiments in which
242 we relate near bed turbulence, as a function of evolving bed roughness, to patterns of erosion and
243 deposition. In all three experiments presented here, channel sinuosity influenced patterns of erosion and
244 deposition. Although the currents used in all three case displayed shear stresses high enough to suspended
245 sediment, the temporal evolution in the turbulence near-bed boundary layer was also very important in
246 deciding whether the channel evolved through erosion or deposition. In the experiments where the
247 boundary layer was transitionally rough the channel evolved through erosion, developing a roughened
248 bed. In both cases, the near-bed boundary layer roughened from smooth or transitionally rough to rough,
249 enhancing near-bed turbulence. When the channel substrate was cohesive, the channel bed evolved
250 through detachment-limited erosion and most of the sediment left the system in suspension. The channel
251 bed was patterned by erosional bedforms, grooves, inner-bank terraces and a semi-continuous inner
252 channels. When the sediment was non-cohesive, the erosion was limited by the ability of the currents to
253 transport sediment and the channel bed evolved into trains of ripples. In contrast, the channel with a
254 hydraulically smooth boundary layer evolved through consistent deposition and the boundary layer
255 appears to have remained hydraulically smooth. To our knowledge, this work presents the first instance in
256 which detachment-limited erosional channels with realistic sediment transport patterns and sediment-
257 turbulence interactions have been designed successfully in laboratory settings. Our results suggest that
258 erosion in submarine channels is a self-reinforcing mechanism whereby developing bed roughness
259 increases turbulence at the boundary layer, enhancing erosion and inhibiting deposition; deposition in

260 submarine channels occurs if the boundary layer is smooth, promoting channel aggradation and loss of
261 channel relief.

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409 **Figures and captions:**

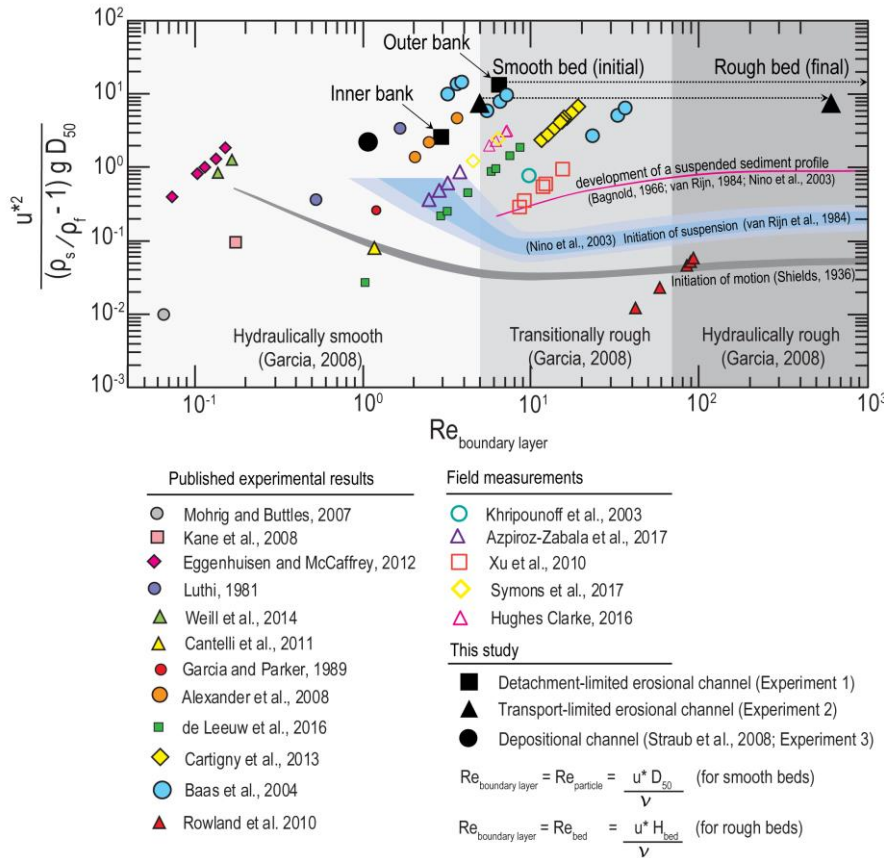


Figure 2: The modified Shield’s scaling approach of de Leeuw et al., 2016, used here to compare our experiments to various experimental and field studies. Note that the initial conditions in all 3 experiments presented in this study span the threshold between hydraulically smooth and transitionally rough flow. Bed roughness

423 that evolved in Experiments 1 and 2 increased the turbulence in the boundary, causing it to become
 424 hydraulically rough. (Luthi, 1981; Garcia and Parker, 1989; Khripounoff et al., 2003; Baas et al., 2004;
 425 Mohrig and Buttles, 2007; Alexander et al., 2007; Straub et al., 2008; Kane et al., 2008; Xu, 2010;
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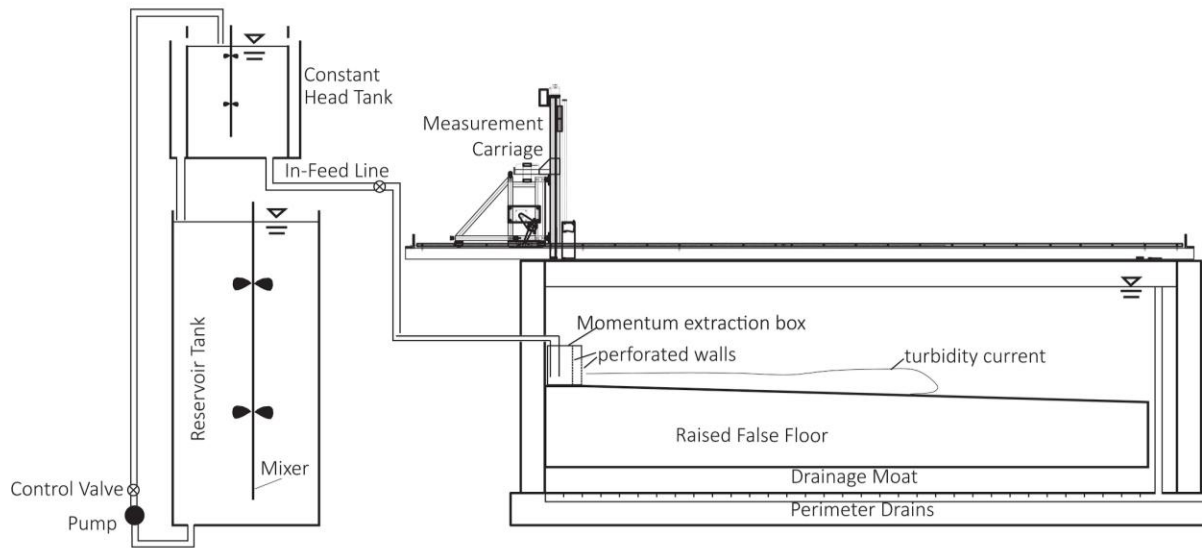


Figure 2: A generalized schematic of the experimental basin set-up used for the three experiments.

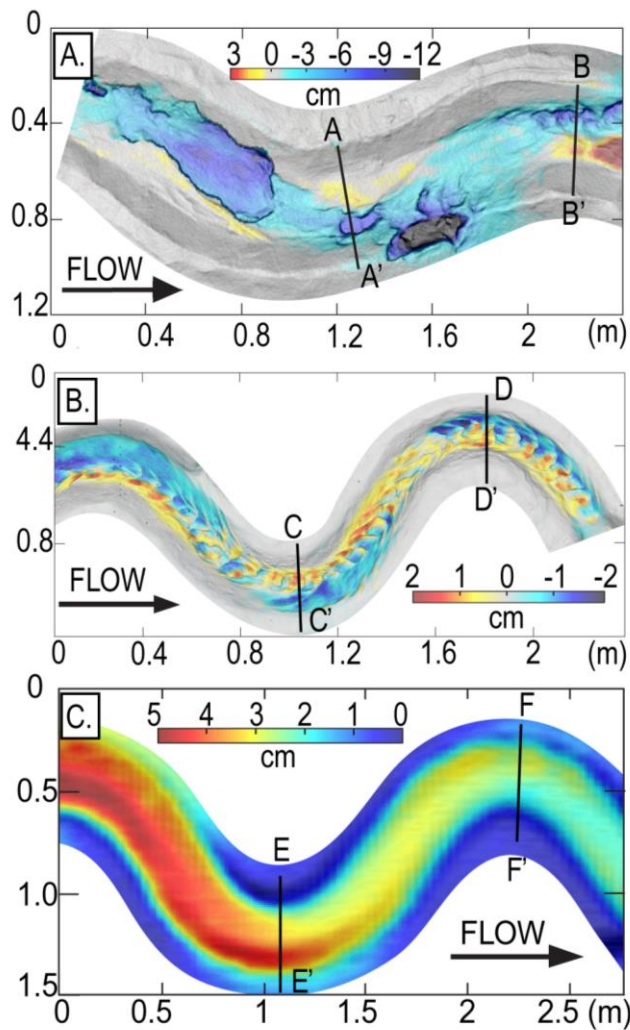


Figure 3: Difference maps defining net elevation change in all three experiments.. (A) Detachment-limited erosion in Experiment 1 resulted in a rough bed patterned with erosional bedforms along a semi-continuous erosional inner channel that followed the path of the high velocity core, and terraces formed at inner banks. (B) Transport-limited erosion in Experiment 2 resulted in a semi-continuous mobile sediment bed, reworked into ripples. (C) Consistent deposition in Experiment 3 resulted in a channel that was persistently aggradational, with the thickest deposits at the outsides of bends.

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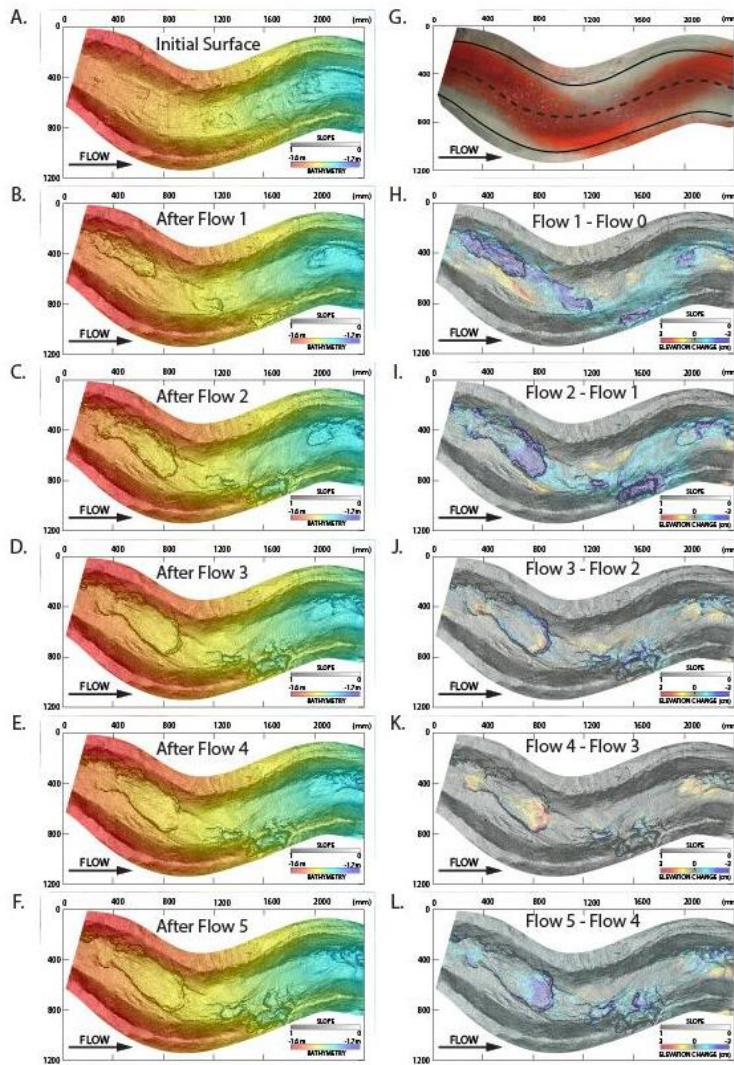


Figure 4: (A-F) Experiment 1 time-lapse laser-scanned topographic maps showing how the 5 experimental currents evolved the experimental channel. (G) Orthorectified overhead photograph showing the pathway of the high velocity core of the current-tracked by red dye with the most intensity. The very small amounts of red dye near the inner banks bear testament to very low velocities in these zones. (H-L) is a series of difference maps that define patterns of erosion and deposition within the experimental channel due to the passage of the 5 density currents. Note how erosion (cold colors) tracks the

465 pathway of the high velocity core (intense red dye in G) and no erosion weak deposition (warm colors) is
466 associated with inner bank zones visited by separated flow (low amount of red dye in G).

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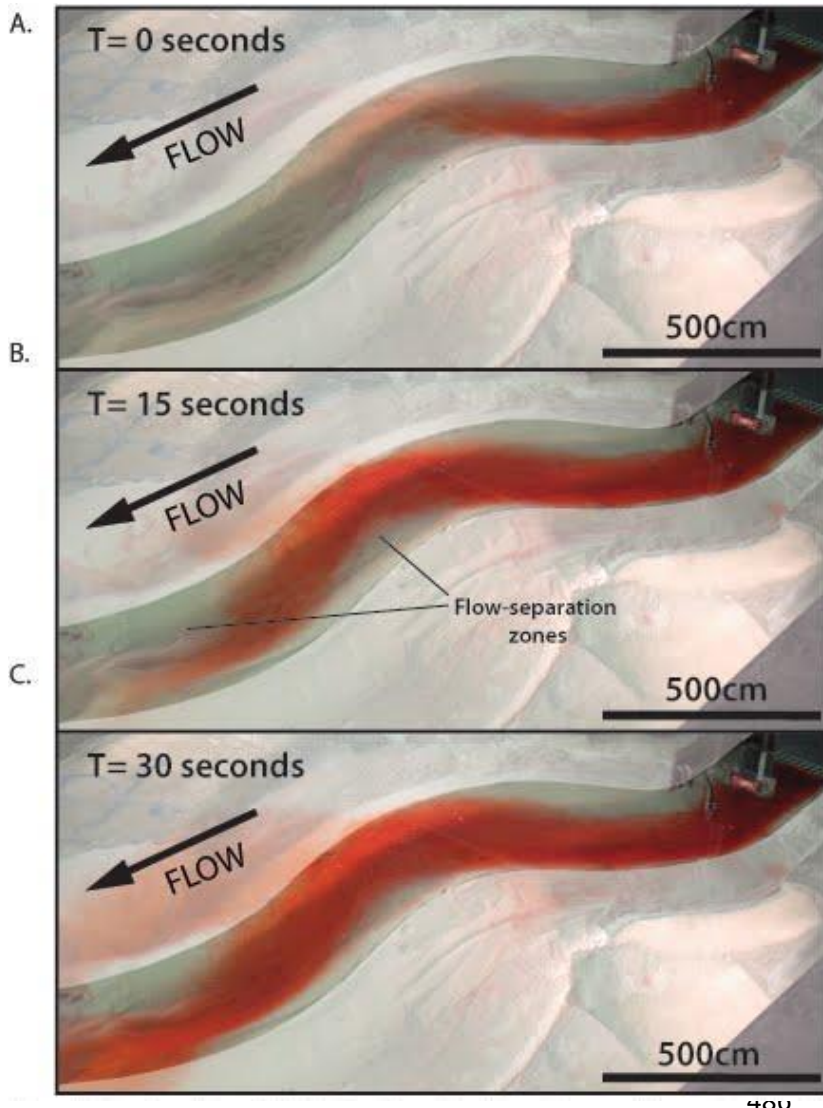
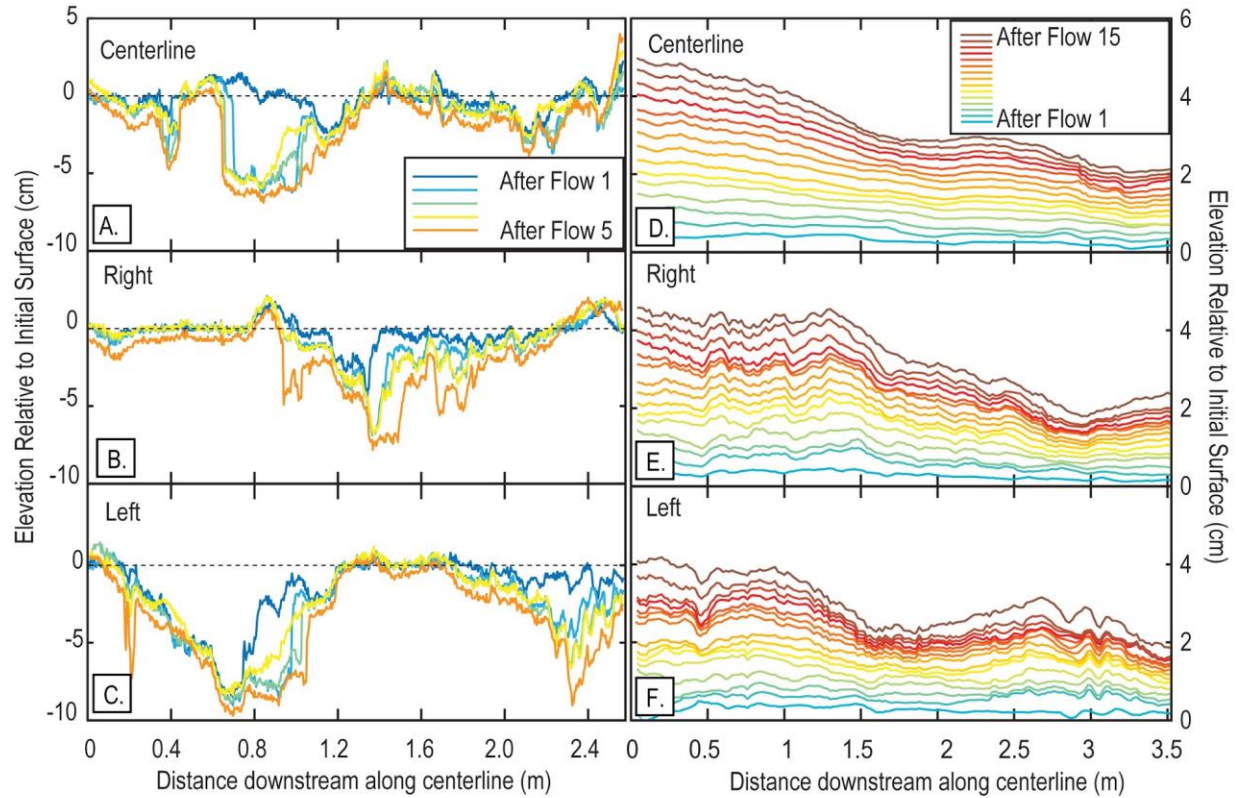


Figure 5: A-C Time lapse photographs showing a pulse of red dye in the current that defines the pathway of the high-velocity core of the current. Low velocity zones where flow separated from the inner banks received the dyed current later than the outside of bends and the dye intensity was always lower than at the outside of bends.

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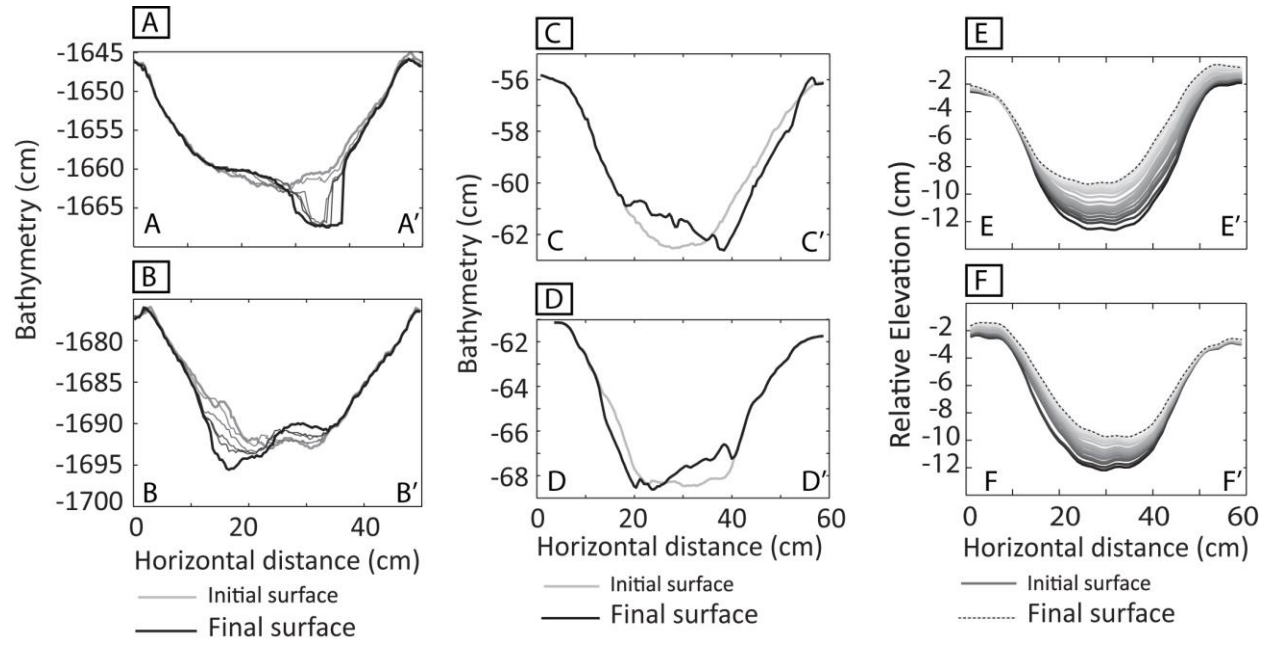
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491 Figure 6: A-C) Change in elevation of the channel bed in Experiment 1 after the passage of 5 consecutive
492 flows, along (A) the centerline, (B) 15 cm right of the centerline, and (C) 15 cm left of the centerline. D-
493 F) Change in elevation of the channel bed in Experiment 3 after the passage of 15 consecutive flows,
494 along (A) the centerline, (B) 5 cm right of the centerline, and (C) 5 cm left of the centerline.

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499 Figure 7: Cross sections showing time-lapse topographic evolution at the apices of the second and third
500 bends in Experiment 1 (A-B), Experiment 2 (C-D) and Experiment 3 (E-F).