

1 Is fine sediment in sandy riverbed deposits a proxy for paleo-
2 sediment supply?

3 **Nathaniel Wysocki¹ and Elizabeth Hajek^{1,*}**

4 ¹*Department of Geosciences, Pennsylvania State University, 503 Deike Building, University*
5 *Park, PA 16802*

6 **Corresponding Author*

7 **ABSTRACT**

8 The amount of silt and clay supplied to rivers can be a primary control on the form and dynamics
9 of channel networks, and it affects the distribution and interconnectedness of buried fluvial
10 reservoirs. Despite its importance, it is difficult to reconstruct how much fine sediment was
11 supplied to ancient rivers. The presence of silt and clay accumulations in sandy river deposits is
12 often interpreted as an indication of variability in flow conditions due to seasonal stagnation or
13 tidal influence, but it has not been tested whether these deposits can be used to evaluate how
14 much fine sediment was transported in ancient rivers. Here we report results from a series of
15 experiments designed to evaluate how much clay and silt are preserved in sandy riverbed
16 deposits under constant and variable discharge conditions. Our results demonstrate that 1) clay-
17 silt deposits, including drapes and lenses, form under constant high-discharge conditions, 2) the
18 amount of fine sediment recovered from bed-material deposits is higher when more fine
19 sediment is supplied, and 3) the fraction of fine sediment trapped during bed aggradation is
20 higher than what is retained during bypass conditions. These results confirm that fine-sediment
21 accumulations are not unique indicators of variable flow conditions and that the net retention of

22 clay and silt in sandy riverbed deposits may be more indicative of the overall amount of fine
23 sediment supplied to a river.

24 **INTRODUCTION**

25 Understanding how clay and silt are deposited and stored in riverbed sediments is
26 important for a range of geologic and river-management issues. In modern rivers, the amount and
27 distribution of fine sediment in riverbeds impacts riverine habitats, contaminant transport and
28 leaching, and engineering decisions (e.g., Downs et al., 2009; Draut and Ritchie, 2015; Hamm et
29 al., 2011; Packman and Brooks, 2001; Wooster et al., 2008). In ancient deposits, the abundance
30 and distribution of mud accumulations control the quality and connectivity of fluvial aquifers
31 and hydrocarbon reservoirs (e.g., Bierkens and Weerts, 1994; Jackson et al., 2005), and are
32 useful for interpreting paleoenvironmental conditions in ancient fluvial systems, including the
33 variability or seasonality of discharge (e.g., Plink-Bjorklund, 2015) and the long-term balance of
34 sediment accumulation relative to river mobility (e.g., Hampson et al., 2012). Additionally, there
35 are important outstanding questions about the influence of clays on channel dynamics (e.g.,
36 Matsubara et al., 2015). The ability to reconstruct the relative abundance of clay supplied to
37 ancient rivers on Earth or other planets would help answer these questions and improve
38 paleoenvironmental reconstructions from sedimentary deposits.

39 Because fine sediment can be transported with relatively low flow velocities and has a
40 slow settling velocity, clay and fine silt accumulations in channel-bed deposits are often
41 interpreted as indicating periods of very low flow or standing water. Consequently, clay drapes
42 and lenses within ancient channel deposits are commonly cited as evidence of tidal influence,
43 seasonal stagnation, or waning flows (e.g., Bhattacharya, 1997; Martin, 2000; Plink-Bjorklund,
44 2015; Steel et al., 2011). However, studies have shown that fine sediment can be incorporated

45 into porous beds under high discharge conditions (e.g., Baas et al., 2016; Packman and MacKay,
46 2003). This raises the question of how to differentiate fine-sediment accumulations formed under
47 variable or low discharge from those deposited under higher discharge conditions. Furthermore,
48 if fine sediments are routinely incorporated into fluvial bed material under a range of flow
49 conditions, the fraction of fine sediment preserved in ancient fluvial deposits may be useful for
50 reconstructing the proportion of fines supplied to ancient river systems.

51 The presence of fine sediment can significantly influence sediment transport and flow
52 conditions in channels. High clay concentrations can alter the structure of turbulent flows,
53 suppressing turbulence completely when concentrations are high enough, and clay in channel
54 beds can increase the effective shear stress necessary to erode the bed (Baas et al., 2016).
55 Together these effects can change the scale, shape, and migration rate of bedforms, and
56 ultimately may influence the character of sedimentary deposits from flows with high clay loads
57 (e.g., Baas et al., 2011). The stratigraphic manifestation of the effects of clay on bedform
58 morphodynamics is still being evaluated. In particular, for fully turbulent flows, it remains
59 unclear whether differences in supplied clay concentrations in can be recorded in bed-material
60 deposits formed under constant discharge.

61 We conducted a series of experiments to evaluate whether clay deposition occurs in
62 sandy river beds under fully turbulent high-discharge conditions, and whether the amount of clay
63 found in bed deposits is related to the amount of clay supplied to the flow. The experiments were
64 designed to explore whether the amount of fine-sediment supplied to a flow affects the amount
65 and distribution of fine-sediment accumulations in the bed and whether variable flow conditions
66 significantly enhance the amount of fine-sediment deposited and stored in sandy river beds.

67 **EXPERIMENTAL DESIGN**

68 We performed a series of five experiments in a feed-style flume at the St. Anthony Falls
69 Laboratory (University of Minnesota; Figure 1). Water and sediment discharge were set to
70 aggrade a sand bed via a wedge of sediment that prograded down the flume during each run; this
71 is analogous to a bar with superposed bedforms migrating downstream in a river. Sand
72 ($D_{50}=0.343$ mm) and kaolin clay ($D_{50}= 0.004$ mm) were supplied to the flume at a constant rate.
73 A clay slurry, with different concentrations for each run, was added to the flume at a rate of 1 l/s.
74 Total water discharge for each run was 21 l/s and was monitored an acoustic Doppler
75 velocimeter (ADV) and by measuring the water depth over the weir at the end of the flume.
76 Water exited the end of the flume over a weir that was fixed, allowing the bed to aggrade during
77 each run. Sand discharge was set at 15.0 g/s in all runs. The bed aggraded to the weir elevation in
78 about four hours and each run was continued at bypass for 15 to 30 minutes.

79 Three runs had constant water discharge but different clay concentrations and one run
80 had variable water discharge (Table). Discharge for all runs was sufficient to transport clay as
81 wash load and the sand was transported in the suspended-load regime, consistent with natural
82 sand bed systems where bed material $D_{50} \leq 0.50$ mm is often transported in suspension
83 (Wilkerson and Parker, 2011) and all runs were equivalent to the fully turbulent flows of Baas et
84 al. (e.g., 2016). The four constant-discharge runs had clay concentrations of 0.0, 1000, 4000,
85 8500 mg/l. The variable-discharge experiment had low clay concentration (1000 mg/l) and water
86 and sediment discharge were slowed and stopped every hour, allowing fine sediment to settle
87 onto the bed.

88 Each run was recorded from the side of the flume with a video camera and photographs.
89 These images were used to reconstruct bed topography and measure bed aggradation and
90 bedform scale in each run. After each experiment, the bed was dried for two days then

91 excavated. Fine-sediment accumulations were mapped on photographs of the flume wall and
92 samples were collected from bed deposits that accumulated during the aggradational and bypass
93 phases of the experiment. Sediment samples were wet-sieved to determine the fraction of fine
94 sediment. These values were combined with mapped fines accumulations to compare the amount
95 of clay deposited in the bed throughout each run.

96 Experimental parameters and analyses are detailed in Supplementary Material along with
97 links to videos of each run.

98 **RESULTS**

99 Fine-sediment accumulations in experimental bed deposits included lenses, drapes, and
100 intercalated (interstitial) fines (Figure 2). Visible clay accumulations were most prominent in
101 deposits from the high-concentration run, with most of the bed showing intercalated fines and
102 numerous bedform-scale lenses and continuous drapes of fine sediment. Interstitial clay was less
103 noticeable in the intermediate-discharge run, but bed deposits contained clay lenses and some
104 continuous clay drapes. Bed deposits from the low-concentration run contained some clay
105 drapes. Discontinuous clay drapes formed in deposits of the variable discharge run.

106 The proportion of clay in bed-material deposits increased with higher clay concentrations
107 (Table). For all but the low-concentration constant-discharge run, the weight percent of clay
108 significantly exceeded what would be expected if clay retention were only due to interstitial clay
109 filling bed pore volume at the same concentration as the flow. Additionally, the aggradational
110 phase showed substantially higher clay retention than the bypass phase in all runs. Bed-deposit
111 samples from the variable-discharge run showed higher clay retention than the constant-
112 discharge run with the same clay concentration.

113 **DISCUSSION**

114 The experiments run under constant, high-discharge conditions produced deposits similar
115 to those typically considered diagnostic of variable flow conditions (e.g., clay drapes and flaser-
116 like bedding). This suggests that the presence of clay drapes and lenses in channel deposits is an
117 insufficient gauge of discharge intermittency or tidal influence in ancient rivers without other
118 compelling evidence. Despite having a relatively low clay concentration, the variable-discharge
119 experiment retained more clay than its constant-discharge counterpart. Clay drapes that formed
120 in the variable-discharge run tended to be discontinuous because of erosion that occurred during
121 re-activation of the bed as discharge increased. This suggest that the character of clay
122 accumulations from truly intermittent flows might be differentiable from those generated in
123 rivers with more constant discharge. However, results of these experiments suggest that the
124 overall flux of fine-sediment through a system may be a dominant control on total fine-sediment
125 retention in sandy riverbeds.

126 Clay in these experiments should have been transported as wash load and had limited
127 interaction with the bed; however fine sediment was routinely deposited and preserved along
128 with sandy bed material. These experiments were run in freshwater with kaolinite clay. Although
129 such conditions are not strongly associated with flocculation, some clay aggregates were
130 observed in each experiment and may have contributed to clay accumulation in the bed
131 (Supplemental Videos). However, the majority of clay moving through the flume was suspended
132 uniformly throughout the water column, so aggregates may not have been the primary source of
133 clay extraction from the flow to the bed. Fine-sediment accumulations were most prevalent on
134 the lee sides of individual bedforms downstream of the sediment wedge (e.g., Figure 2). This
135 pattern contrasts with clay accumulation observed in some experiments where advective
136 pumping and hyporheic exchange cause clay to be incorporated into the upstream side of dunes

137 (e.g., Packman and MacKay, 2003), and suggests that the presence of the sediment wedge
138 facilitated clay deposition in the experiments.

139 The sediment wedge may have initiated a flow-separation zone at its crest which might
140 have promoted clay deposition in a recirculation zone immediately downstream of the wedge
141 front. The prograding wedge also locally sequestered sand in the flume during the aggradational
142 phase of the experiment. The lower effective sand flux downstream of the wedge resulted in
143 bedform-migration rates that were ~8 times slower during the aggradation phase (1.1-1.8 cm/s)
144 than the bypass phase (8.6-12.0 cm/s). Although the concentration of clay supplied to the flow
145 was constant throughout the runs, downstream of the wedge the concentration of clay relative to
146 sand was much higher in the aggradational phase than the bypass phase. Enhanced fine-sediment
147 deposition downstream of the sediment wedge is consistent with field data showing silt and clay
148 accumulations downstream of bars in modern rivers and ancient deposits (Hajek et al., 2011;
149 Lynds and Hajek, 2006).

150 The preservation of accumulated fine sediment (and bed material in general) was likely
151 enhanced by an abrupt increase in local aggradation as the sediment wedge passed a given
152 location in the flume. In field-scale systems bar progradation might rapidly bury slower-moving
153 bedforms, thereby preserving them entirely. This contrasts the partial preservation of relatively
154 fast-moving bedforms (i.e. the lowermost portion of some bedforms are preserved) due to
155 stochastic variation in dune height (e.g., Paola and Borgman, 1991) or slow long-term
156 aggradation (e.g., Leclair, 2002). Collectively, the results of our experiments suggest that, at field
157 scales, morphodynamics of larger features like bars may play a significant role in controlling the
158 deposition and preservation fine sediment and bed material in rivers.

159 These results have important implications for interpreting ancient fluvial deposits. First,
160 the fraction of fine sediment preserved in ancient bed-material deposits may reflect the amount
161 of fine sediment supplied to a watershed. This means that relative differences in the proportion of
162 fine sediment within channel-bed sandstones may be useful for determining which ancient fluvial
163 systems had particularly mud-prone sediment sources, especially when coupled with
164 observations about the abundance, geometry, and preservation of reach-scale fine-sediment
165 deposits like inter-bar mudstones and floodplain deposits (e.g., Lynds and Hajek, 2006). This
166 information may be useful for testing hypotheses about relative cohesion among ancient systems
167 and the relationship between clay supply and fluvial planform (e.g., van Dijk et al., 2013).
168 Furthermore, constraining the fraction of fines present bed-material deposits will be helpful for
169 more accurately predicting heterogeneity and compartmentalization in fluvial reservoirs. More
170 work is needed to determine whether quantitative paleosediment-flux reconstructions could be
171 achieved, but in the near term, these results indicate that the amount of silt and clay preserved in
172 riverbed deposits may be sufficient for relative comparisons among ancient rivers and testing
173 hypotheses about which systems had high vs. low clay and silt supplies.

174 **CONCLUSIONS**

175 Results of these experiments demonstrate that 1) low discharge is not a necessary
176 condition for clay deposition in active river beds, 2) clay deposition increases with clay supply,
177 and 3) clay retention in the bed is significantly higher during periods of bed aggradation than
178 sediment bypass, particularly when aggradation is facilitated by bar migration. While variable
179 discharge may enhance clay deposition for a given fine-sediment flux, our results show that
180 significant fine-sediment accumulations in ancient channel deposits may primarily reflect
181 supplied wash load rather than highly variable discharge, as is often interpreted. This indicates

182 that interpreting high discharge variability, for example tidally influenced flows or seasonal
183 stagnation, requires evidence beyond clay deposits. Our results suggest that the presence of
184 migrating bar forms may facilitate clay deposition and preservation during high flow conditions.
185 Measuring the concentration of clay in ancient river-bed deposits may provide an important
186 avenue for reconstructing paleo-sediment supply, particularly the relative abundance of clays and
187 silts transported by a system; this is a critical variable necessary for understanding past changes
188 in source material or weathering rates and evaluating the how clay contributed to cohesion on
189 ancient landscapes and on other planets.

190 **APPENDIX**

191 Supplemental data submitted.

192 **ACKNOWLEDGMENTS**

193 Support for this research was provided by the donors of the American Chemical Society
194 Petroleum Research Fund, NSF Award #1455240, and student support from the Geological
195 Society of America, American Association of Petroleum Geologists, and Penn State Geosciences
196 to N.W. Without the incredible expertise and generosity of SAFL personnel, particularly Ben
197 Erickson and Sara Mielke this work would not have been possible. We are grateful to E.
198 Chamberlin and Macalester College students for helping run the experiments and thank C. Paola,
199 R. Slingerland, T. Bralower, R. DiBiase, E. Greenberg, and S. Trampush for helpful discussions,
200 and J. Pizzuto and M. Perillo for thoughtful and constructive reviews.

201 **REFERENCES CITED**

- 202 Baas, J. H., Best, J. L., and Peakall, J., 2011, Depositional processes, bedform development and
203 hybrid bed formation in rapidly decelerated cohesive (mud-sand) sediment flows:
204 *Sedimentology*, v. 58, p. 1953-1987.
205 Baas, J. H., Best, J. L., and Peakall, J., 2016, Predicting bedforms and primary current
206 stratification in cohesive mixtures of mud and sand: *Journal of the Geological Society of*
207 *London*, v. 173, p. 12-45.

208 Bhattacharya, A., 1997, On the origin of non-tidal flaser bedding in point bar deposits of the
 209 river Ajay, Bihar and West Bengal, NE India: *Sedimentology*, v. 44, p. 973-975.

210 Bierkens, M. F. P., and Weerts, H. J. T., 1994, Block hydraulic conductivity of cross-bedded
 211 fluvial sediments: *Water Resources Research*, v. 30, no. 10, p. 2665-2678.

212 Downs, P. W., Cui, Y., Wooster, J. K., Dusterhoff, S. R., and Booth, D. B., 2009, Managing
 213 reservoir sediment release in dam removal projects: An approach informed by physical
 214 and numerical modelling of non-cohesive sediment: *International Journal of River Basin
 215 Management*, v. 7, no. 4, p. 433-452.

216 Draut, A. E., and Ritchie, A. C., 2015, Sedimentology of new fluvial deposits on the Elwha
 217 River, Washington, USA, formed during large-scale dam removal: *River Research and
 218 Applications*, v. 31, p. 42-61.

219 Hajek, E. A., Lynds, R., and Huzurbazar, S., Comparing particle-size distributions in modern and
 220 ancient sand-bed rivers, *in Proceedings AGU Fall Meeting, San Francisco, 2011,*
 221 *American Geophysical Union.*

222 Hamm, N. T., Dade, W. B., and Renshaw, C. E., 2011, Fine particle deposition to porous beds:
 223 *Water Resources Research*, v. 47, no. 11, p. n/a-n/a.

224 Hampson, G. J., Royhan Gani, M., Sahoo, H., Rittersbacher, A., Irfan, N., Ranson, A., Jewell, T.
 225 O., Gani, N. D. S., Howell, J. A., Buckley, S. J., and Bracken, B., 2012, Controls on
 226 large-scale patterns of fluvial sandbody distribution in alluvial to coastal plain strata;
 227 Upper Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, USA:
 228 *Sedimentology*, v. 59, no. 7, p. 2226-2258.

229 Jackson, M. D., Yoshida, S., Muggeridge, A. H., and Johnson, H. D., 2005, Three-dimensional
 230 reservoir characterization and flow simulation of heterolithic tidal sandstones: *AAPG
 231 Bulletin*, v. 89, no. 4, p. 507-528.

232 Leclair, S., 2002, Preservation of cross-strata due to the migration of subaqueous dunes: an
 233 experimental investigation: *Sedimentology*, v. 49, p. 1157-1180.

234 Lynds, R., and Hajek, E., 2006, Conceptual model for predicting mudstone dimensions in sandy
 235 braided-river reservoirs: *AAPG Bulletin*, v. 90, no. 8, p. 1273-1288.

236 Martin, A. J., 2000, Flaser and wavy bedding in ephemeral streams: a modern and ancient
 237 example: *Sedimentary Geology*, v. 136, p. 1-5.

238 Matsubara, Y., Howard, A. D., Burr, D. M., Williams, R. M. E., Dietrich, W. E., and Moore, J.
 239 M., 2015, River meandering on Earth and Mars: A comparative study of Aeolis Dorsa
 240 meanders, Mars and possible terrestrial analogs of the Usuktuk River, AK, and the Quinn
 241 River, NV: *Geomorphology*, v. 240, p. 102-120.

242 Packman, A. I., and Brooks, N. H., 2001, Hyporheic exchange of solutes and colloids with
 243 moving bed forms: *Water Resources Research*, v. 37, no. 10, p. 2591-2605.

244 Packman, A. I., and MacKay, J. S., 2003, Interplay of stream-subsurface exchange, clay particle
 245 deposition, and streambed evolution: *Water Resources Research*, v. 39, no. 4.

246 Paola, C., and Borgman, L. E., 1991, Reconstructing random topography from preserved
 247 stratification: *Sedimentology*, v. 38, no. 4, p. 553-565.

248 Plink-Bjorklund, P., 2015, Morphodynamics of rivers strongly affected by monsoon
 249 precipitation: Review of depositional style and forcing factors: *Sedimentary Geology*, v.
 250 323, p. 110-147.

251 Steel, R. J., Plink-Bjorklund, P., and Aschoff, J., 2011, Tidal deposits of the Campanian Western
 252 Interior Seaway, Wyoming, Utah and Colorado, USA, *in Davis, R. A. J., and Dalrymple,*
 253 *R. W., eds., Principles of Tidal Sedimentology: Netherlands, Springer, p. 437-471.*

254 van Dijk, W. M., van de Lageweg, W. I., and Kleinmans, M. G., 2013, Formation of a cohesive
255 floodplain in a dynamic experimental meandering river: *Earth Surface Processes and*
256 *Landforms*, v. 38, no. 13, p. n/a-n/a.
257 Wilkerson, G. V., and Parker, G., 2011, Physical basis for quasi-universal relationships
258 describing bankfull hydraulic geometry of sand-bed rivers: *Journal of Hydraulic*
259 *Engineering*, v. 137, no. 7, p. 739-753.
260 Wooster, J. K., Dusterhoff, S. R., Cui, Y., Sklar, L. S., Dietrich, W. E., and Malko, M., 2008,
261 Sediment supply and relative size distribution effects on fine sediment infiltration into
262 immobile gravels: *Water Resources Research*, v. 44, no. 3, p. n/a-n/a.
263

264 **FIGURE CAPTIONS**

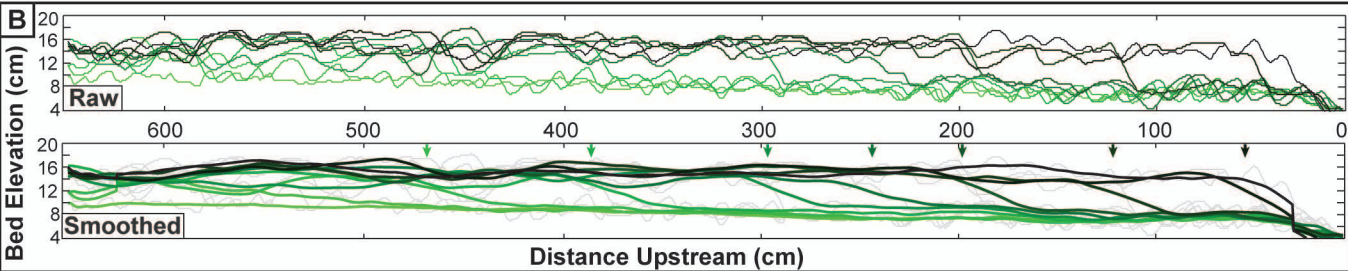
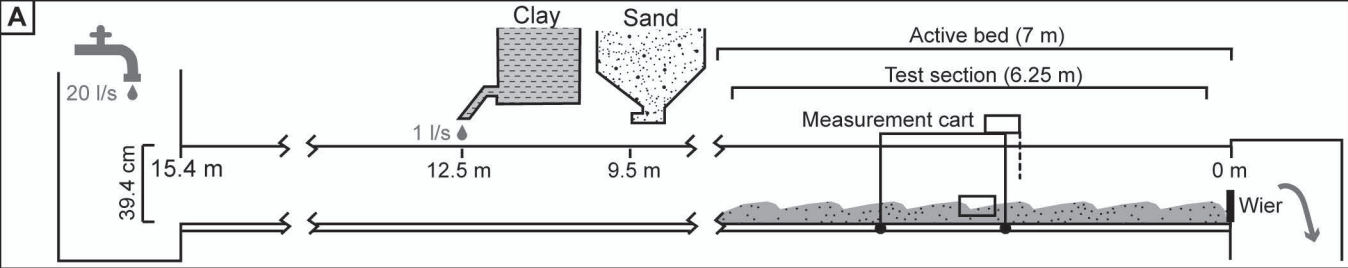
265 **Figure 1.** A) Diagram of experimental setup showing flume extent and the location of clay and
266 sand delivery; water entered the flume on the left side and exited over the weir on the right side.
267 Sand was supplied dry and clay was delivered from a mixing tank at different concentrations in
268 each run at a rate of 1 l/s. Data reported here come from the active bed region. The measurement
269 cart included sediment-sampling and ADV equipment (at 2.9 m) and videos and photographs
270 were taken from through the sidewall of the flume at 3.25 m. B) Example of bed evolution in the
271 Test Section of the flume during the Intermediate Concentration run (3x vertical exaggeration).
272 Lines show bed topography every 30 minutes through the experiment (progressing from light
273 green to dark green). Raw panel shows the full bed topography and the smoothed panel shows
274 the same data averaged with a moving window of two average bedform lengths (50 cm). Arrows
275 indicate the approximate position of the front of the sediment wedge at each time. All runs
276 showed the same bed evolution; complete bed-evolution histories and experimental details are
277 included in the supplemental material.

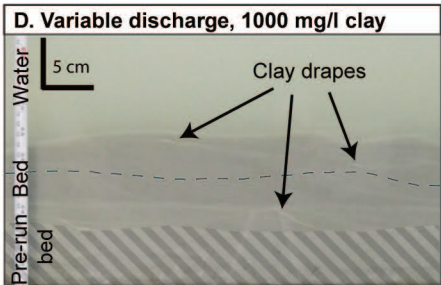
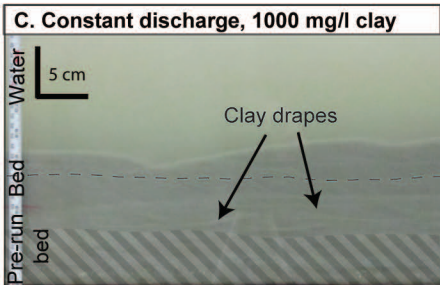
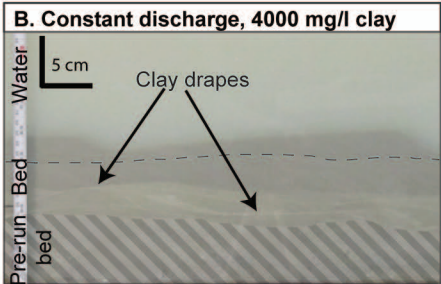
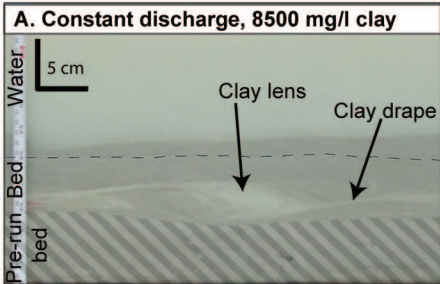
278 **Figure 2.** Example clay-deposit types found in experimental beds. Striped region defines the pre-
279 run bed and the dashed line shows the transition from aggradation-phase deposits (below) to
280 bypass-phase deposits (above). The high-concentration, constant-discharge run (A) had the
281 largest visible clay deposits in the form of lenses and abundant continuous clay drapes. The

282 intermediate-concentration run (B) had smaller, less predominant clay lenses and continuous clay
283 drapes. The low-concentration run (C) lacked clay lenses and had thin clay drapes. The variable-
284 discharge run (D) showed more prominent clay drapes than its constant-discharge counterpart
285 (C), but drapes were relatively discontinuous compared to those observed in other constant-
286 discharge runs. All runs also contained intercalated, interstitial clay that was distributed
287 throughout the bed.

288 **Table.** Summary of experimental bed deposit characteristics. Fine-sediment concentration is the
289 concentration of clay in the flow during each run. Fine sediment deposits describe the dominant
290 types of fine-sediment accumulations mapped in each experimental bed (Figure 2). Expected
291 weight percent of fine sediment in the bed samples is the amount of interstitial clay expected in
292 bed pore waters given the supplied concentration for each run. Aggradation and bypass fine
293 sediment weight percent are the average of samples from each phase of each run. Full bed maps
294 and sample data are included in the supplemental material, along with details of a constant-
295 discharge control run that contained no supplied clay.

296 ¹GSA Data Repository item 201Xxxx, supplementary data including details of experimental
297 conditions and analyses, is available online at www.geosociety.org/pubs/ft20XX.htm, or on
298 request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder,
299 CO 80301, USA.





	Fine-sediment concentration	Fine-sediment deposits	Fines in bed samples [wt%]		
			Expected	Aggradation	Bypass
Low concentration	1000 mg/l	Intercalated fines	0.02	0.06	0.05
Intermediate concentration	4000 mg/l	Drapes, intercalated fines	0.08	0.8	0.2
High concentration	8500 mg/l	Drapes, lenses, intercalated fines	0.17	2.2	0.4
Variable discharge	1000 mg/l	Discontinuous drapes, intercalated fines	0.02	0.2	0.1

Data repository and supplemental information for Wysocki and Hajek: Is fine sediment in sandy riverbed deposits a proxy for paleo-sediment supply?

DESCRIPTION OF EXPERIMENTAL PROCEDURES:	2
Description of flume and sediment used in experiments	2
Startup and shutdown procedures	2
LINKS TO VIDEOS OF EACH EXPERIMENTAL RUN	4
EXPERIMENTAL CONDITIONS AND BED EVOLUTION:	5
Table DR1: Summary of experimental conditions and bed evolution for each run.	5
Table DR2: Run and stop (settling) times for the Variable Discharge run	5
Figure DR1: Bed aggradation throughout each run.	6
Figure DR2: Histogram of measured bedform heights for each run.	6
Experimental sediment-transport conditions	7
Figure DR3: Shield's diagram (after Wilkerson and Parker (2011)) showing experimental sediment-transport conditions.	7
Fine sediment transport	7
Comparison with of experimental conditions with other flume experiments	8
Table DR3: Comparison of conditions in this experiment with other mixed sand-clay flume experiments.	8
Figure DR4: Comparison of flow conditions in experiments from this study to the phase diagram presented in Baas et al. (2009).	9
Figure DR5: Comparison of experiments in this study to the clay flow phase diagram of Baas et al. (2009).	9
Figure DR6: Topographic profiles through time of each experiment.	10
Figure DR7: Turbulence intensity calculated from ADV data from each run.	11
Figure DR8: Suspended sediment concentration profiles.	12
Figure DR9: Example images of clay aggregates in experimental runs.	12
DEPOSIT CHARACTERISTICS AND CLAY ACCUMULATIONS:	13
Table DR4: Experimental deposit characteristics and clay-mapping results.	13
BED DEPOSIT SAMPLING	14
Table DR5: Bed-deposit sample locations and weight percent of clay in the sample.	14
Bed Deposit Mapping Description and Images	15
Figure DR10: Photographs and mapped clay accumulations of each run as seen through the glass wall of the flume.	15
REFERENCES	18

DESCRIPTION OF EXPERIMENTAL PROCEDURES:

Description of flume and sediment used in experiments

Experiments were conducted in the 24-in general purpose flume at the St. Anthony Falls Laboratory, University of Minnesota (<http://www.safl.umn.edu/facilities/general-purpose-flumes-6-inch-20-inch-24-inch-flumes>); see Figure 1 in the main manuscript. The flume is a feed style flume 15.42 meters long (50 ft) and 39.97 cm deep (15.5 in). Near the head box the flume is 61 cm and between 14.7 and 12.2 m, the flume narrowed from 61 cm to 30.5 cm. The flume was 30.5 cm-wide for from 12.2 m to the end (0 m) at the weir. The weir height for all runs was fixed at 16 cm. For each run, the initial sediment wedge extended from the outlet of the flume to 8 m and was graded to a slope of 0.004.

The sand feeder was positioned at 8.5 m and the sand feed rate was set at 15.0 g/s (a voltage of 356 on the auger box). This feed rate was verified before each run and prior to sand feed being turned off at the conclusion of each run. Based on water velocity and fall velocity of the median grain diameter sand (0.323 mm) the sand traveled 1.5-1.75 m before reaching the bed. The sand used in these experiments is AGSCO #40-#70 silica sand. This has a narrow distribution with $D_{50}=0.323$ mm, and a sorting coefficient of 1.2. A board was positioned below the feeder to disperse the sand supply, spreading it across the width of the flume.

Clay was delivered to the flume via two mixing tanks. First, clay was fully mixed and wetted in a mixing tank located on the floor above the flume. A clay slurry left this initial mixing tank and was delivered to a second 1 m³ mixing tank positioned just above the flume at 12.5 m. In the second mixing tank, the clay slurry was diluted with city water supplied at a rate of 1 l/s and was mixed via propeller. The dilute clay mixture from the secondary mixing tank was then introduced to the flume at a rate of 1 l/s. Clay was added to the initial mixing tank in volumes that produced the desired final concentration, and the clay slurry was delivered to the secondary mixing tank at a rate to balance the 1 l/s discharge from the secondary mixing tank into the flume. The water level in the tank and sediment feed rate (especially when high) were variable and were monitored and adjusted frequently throughout the course of each run to maintain the appropriate clay concentration in the flume. The clay feed from the secondary take was run over a board to disperse the clay supply uniformly across the width of the flume; this also helped prevent the slurry from becoming a density flow. Clay used in this experiment was Cary Snobrite kaolin clay with a median grain diameter of 0.004 mm. There was no overlap between sand and clay grain size distributions.

The main water supply to the flume Mississippi River water sourced from the St Anthony Falls Lab main channel diversion.

Startup and shutdown procedures

Start-up checklist

- Set initial sediment wedge by scraping off all sediments from prior experiments and grading the slope at 0.004.
- Test sand and clay sediment feed rates.
- Wet sediment wedge for over an hour so that water fills all pore spaces. Using a very low discharge, slowly fill the flume to the level of the weir.
- Start camera.
- Increase the flow to the desired discharge. Lift up on hydraulic pump until plate is at correct location (marked).

- Start clay slurry feed.
 - Turn on hose and sediment feeder in secondary clay mixing tank.
- Turn on sand feed. This starts the official time.
- Note: Ideally clay and sand are turned on at the same time. This can be done with more than one person. The person downstairs turns the hose on, the person upstairs turns the clay feeder on then opens the ball valve. When the slurry enters the flume, the person downstairs turns on the sand feed.
- Check discharge by the water level going over the weir. Should be at 29 cm. if not, adjust discharge with hydraulic pump.

Shut down procedures

- Note time when sediment wedge reaches the weir and the entire bed is at bypass.
- Continue run for 15-30 minutes after this time and begin shut-down.
- Slightly decrease discharge so sand is no longer in suspended load regime.
- Turn off sand feed.
- Turn off clay feed.
 - Shut ball valve, turn off hose, turn off sediment feeder.
- Immediately turn off river water discharge.
- Open drain on the headbox so the flume slowly drains from both sides.
- When bed is drained (still water in the flume, just not above the bed surface) open drain on headbox fully to allow flume to fully drain.
- Turn fan on the bed. Fan is attached to the top of the flume with clips at 1.5 meters blowing upstream.
- Let bed dry over two nights.

Procedures during run

- Collect velocity measurements at 6/10 water depth for 5-10 minutes.
- Collect additional velocity profiles by measuring for one minute at increments of 2 cm water depth from the bed to the top of the flow. (This proved difficult with migrating bedforms.)
- Collect bed and water surface elevation measurements from measuring tape every 50 cm of the test section. Make water surface elevation measurements every 1 meter outside of the test section.
- Take photographs of the test section every 30 minutes (15 minutes after bed and water surface elevations).
 - These are taken 180 cm (~6 ft) away from the flume at points (for the left foot of the tripod) marked on a piece of tape on the floor.
- Suspended sediment samples
 - Samples are taken every 30 minutes by a rake of suspended sediment samplers (Photo), with active tubes spaced 5 cm apart.

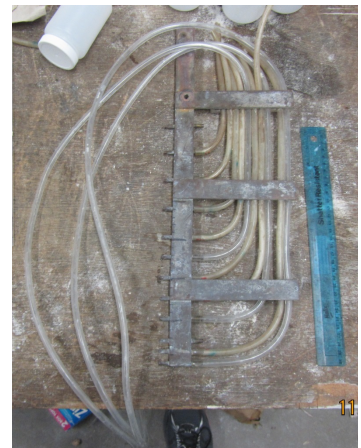


Photo: Suspended sediment sampler

- Suspended sediment samples are collected at the 2 m position in the flume from 3 cm, 8 cm, and 13 cm above the bed.
- Samples are taken by siphoning water through tubes and letting water enter 16 oz containers

- Nearest dune location and dune height are noted
- Active bed material samples
 - Grab samples are taken every 30 minutes (with suspended sediment samples) taken with 8 oz containers.
 - Taken from top few centimeters of closest upstream dune to the 2 m position in the flume.
- Note the time when the prograding wedge reaches the weir and the entire bed is at bypass.
- Continue run for 15- 30 minutes.

Shutdown and startup procedures for variable flow run

- Follow shut-down procedures as normal with the exception of only turning down the clay feed before turning the river water off. Immediately after river water is turned off, shut down clayfeed and let the bed slowly drain naturally. Do not open the valve in the headbox.
- Allow clay to settle for prescribed time.
- To start flume, turn on clay feed to a very low discharge and slowly increase river water discharge (so as not to send a flood wave through the flume eroding the bed). When river discharge is up, turn on clay and sand feed as normal.

LINKS TO VIDEOS OF EACH EXPERIMENTAL RUN

High Concentration Run:

<https://www.youtube.com/watch?v=94O93QsWivU>

https://www.youtube.com/watch?v=_hLRHIIdaPxI

Intermediate Concentration Run:

<https://www.youtube.com/watch?v=wtui5OUFGvw>

<https://www.youtube.com/watch?v=nTdUC845o8Y>

Low Concentration Run:

https://www.youtube.com/watch?v=-fE8_mEmQ0Q

Variable Discharge Run:

<https://www.youtube.com/watch?v=N4nBBHzquIE>

<https://www.youtube.com/watch?v=XZfngqdCwZ8>

EXPERIMENTAL CONDITIONS AND BED EVOLUTION:

Table DR1: Summary of experimental conditions and bed evolution for each run.

Aggradation time is the total time the experiment experienced a net increase in average bed elevation in the test section (starting from the beginning of the experiment) and bypass time is the total time the experiment was run after the bed in the test section fully aggraded (i.e. no net increase in mean bed elevation).

	No Fines	Low Concentration	Intermediate Concentration	High Concentration	Variable Discharge
EXPERIMENTAL CONDITIONS					
Water discharge (l/s)	21	21	21	21	Variable (see Table DR2)
Sand discharge (g/s)	15.0	15.0	15.0	15.0	15.0 (when water discharge > 0)
Clay concentration (mg/l)	0	1,000	4,000	8,500	1,000
Total run time (min)	303	272	277	253	262
Aggradation time (min)	239	239	262	236	247
Bypass time (min)	64	33	15	17	15
BED EVOLUTION					
Bed aggradation rate (cm/min)	0.024	0.025	0.025	0.025	0.024
Total bed aggradation (cm)	6.1	6.1	6.8	6.4	6.6
Downstream wedge progradation rate (cm/s)	2.4	2.4	2.1	2.8	2.1
Mean bedform height (cm)	2.3	2.5	2.2	2.3	2.2
Bedform height standard deviation	1.5	1.4	1.4	1.2	1.2
Mean bedform migration rate (cm/s)					
Aggradational Phase	---	1.1	1.1	1.8	1.2
Bypass Phase	---	12.0	8.6	11.1	10.2

Table DR2: Run and stop (settling) times for the Variable Discharge run

	Part 1	Part 2	Part 3	Part 4	Part 5
Run time (min)	59	55	56	66	27
Settling time (min)	69	69	1010	179	End of run

Figure DR1: Bed aggradation throughout each run.

Bed elevation is the mean elevation of the bed (e.g., mapped profiles in Manuscript Figure 1 and Figure DR6). High = High Concentration Run, Int = Intermediate Concentration Run, Low = Low Concentration Run, Var = Variable Concentration Run, Nf = No Fines (control) Run.

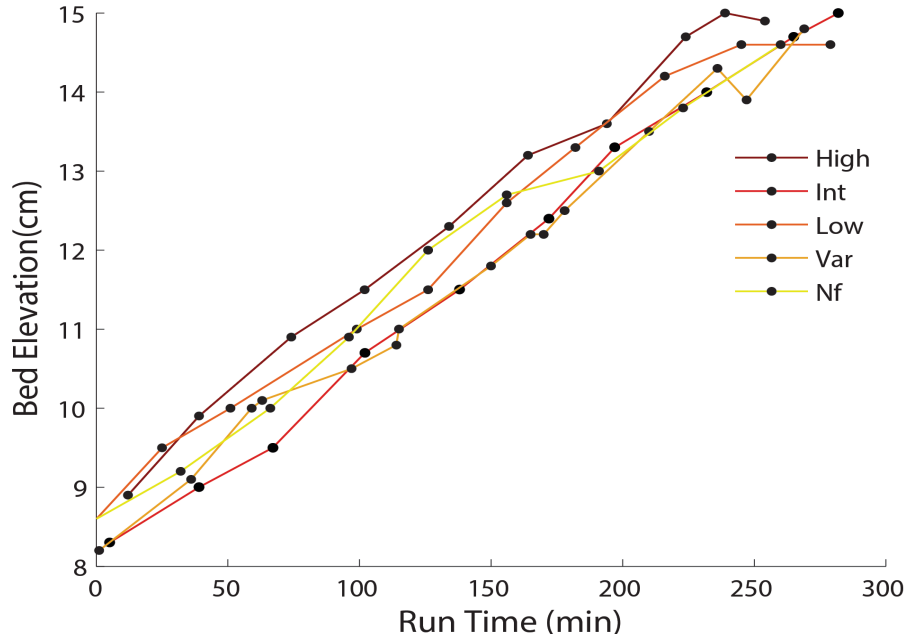
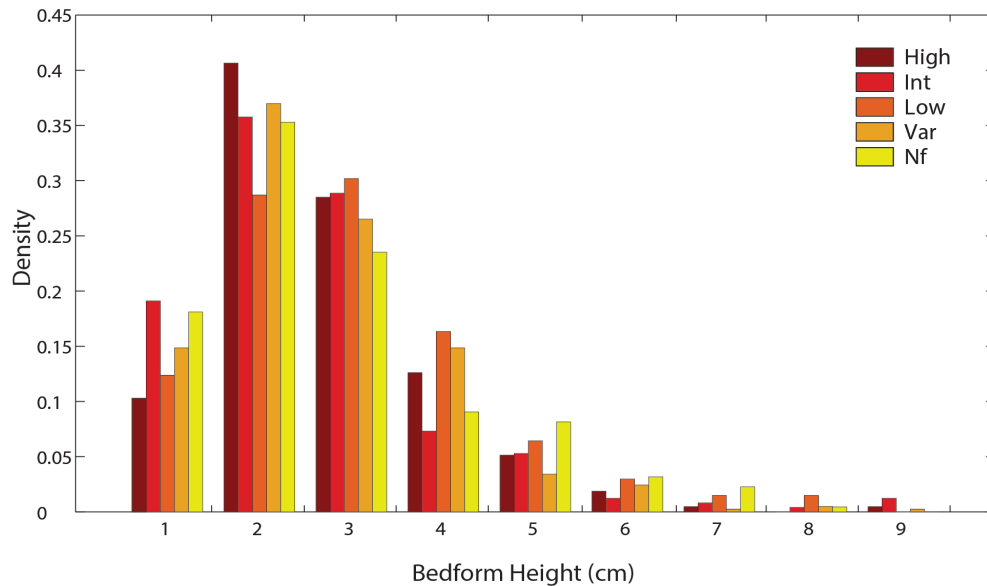


Figure DR2: Histogram of measured bedform heights for each run.

On bed-topography profiles mapped from photos every 30 mins throughout the experiment (Figure DR4), the height (elevation of crest minus elevation of trough) and length (distance between dune crests) of each bedform was measured. Number of bedforms measured for each experiment: No Fines (NF) = 188, Low Concentration (Low) = 202, Intermediate Concentration (Int) = 246, High Concentration (High) = 214, Variable flow (Var) = 420.



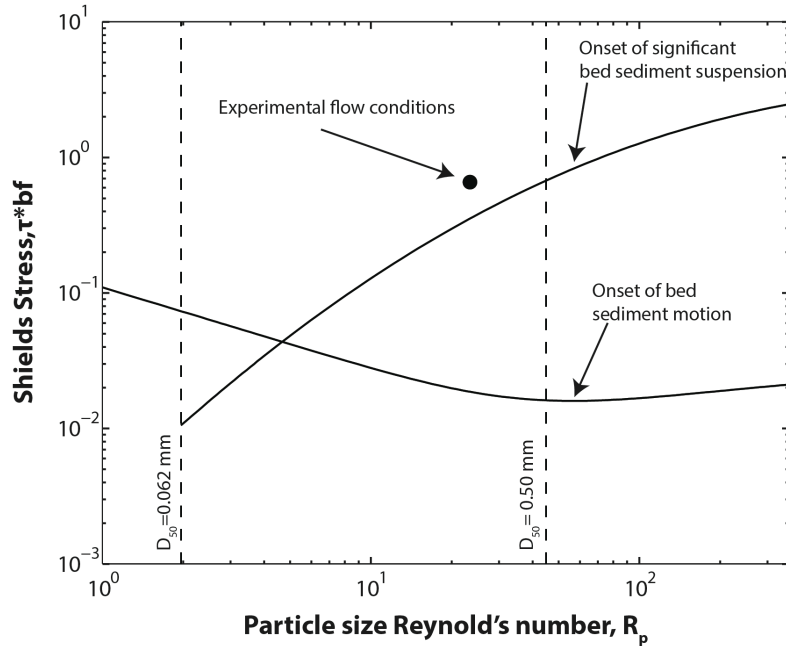
Experimental sediment-transport conditions

Figure DR3: Shield's diagram (after Wilkerson and Parker (2011)) showing experimental sediment-transport conditions.

Shields Stress (τ_{bf}^*) was calculated using Wilkerson and Parker's Equation 13:

$$\tau_{bf}^* = \frac{H_{bf} S}{RD_{50}}$$

where H_{bf} is the flow depth, S is the slope, R is the submerged specific gravity of sediment, and D_{50} is the median grain size.



Fine sediment transport

Fine sediment supplied to the flume should have bypassed the entire flume as wash load. Given the slowest average water discharge in the suite of experiments (40 cm/s), and a settling velocity for clay in freshwater of 0.0002 cm/s (Sutherland et al., 2015), clay introduced at 12.5 m in the flume would have settled only 60 microns through the water column during its transport downstream in the experiments. Additionally, the concentration of clay in these experiments (0.5% by weight) was lower than the concentrations shown to induce significant changes in settling behavior of clay (either through flocculation or hindered settling, e.g., Sutherland et al., 2015) or the turbulence character of the flow (e.g., Baas et al., 2009).

Comparison with of experimental conditions with other flume experiments

Table DR3: Comparison of conditions in this study with other mixed sand-clay flume experiments.

Values for experiments in this study are averages of measurements taken throughout each run. Concentration (C) was imposed in each run. Flow depth (h) for each run is the average water-surface elevation minus the average bed elevation. Average flow velocity (U) was estimated by averaging ADV measurements throughout each run. Slope is the average of measured water-slopes during each run. Froude (Fr) and Reynolds (Re) numbers are estimated using flow depth and velocity and standard values for water density and viscosity. Baas et al. experiments include those that match the experimental conditions of this study most closely. Baas et al. classify the flow structure of their runs using detailed Ultrasonic Doppler velocimetry profiling (listed in Notes column). All data were reported in their 2009 and 2011 papers; slope value for the 2011 run is a bed slope. For Packman and MacKay experiments, slope is reported as “energy grade line”; Fr and Re were not reported in their paper, so we estimated values for each run (*italics*).

	Run	C (mg/l)	h (cm)	U (cm/s)	Slope	Fr	Re	Notes
Wysocki & Hajek (this study)	No Fines (control)	0	17.5	45	0.0018	0.34	78750	Variable Flow Run values are for high flow conditions
	Low Conc.	1000	16.6	50	0.0019	0.39	83000	
	Intermed. Conc.	4000	15.1	40	0.0016	0.33	60400	
	High Conc.	8500	14.9	60	0.0019	0.50	89400	
	Variable Flow	1000	16.2	46	0.0020	0.37	74520	
Baas et al. (2011)	1	5200	15.1	46.5	0.00138	0.38	69939	Turbulent Flow
Baas et al. (2009)	3-1	500	14.5	43.9	0.00018	0.37	63599	Turbulent Flow
	3-2	4000	15.7	42.6	0.00029	0.34	65256	Turbulent Flow
	3-3	9600	15.5	41.4	0.00029	0.34	63473	Turbulence-Enhanced Transitional Flow
	4-2	4000	15.4	55.9	0.00029	0.44	86023	Turbulent Flow
	4-3	9800	15.1	55.7	0.00029	0.43	83182	Turbulent Flow
	5-2	4200	15.0	70.4	0.00029	0.58	105467	Turbulent Flow
Packman and MacKay (2003)	1	230, 460, 230	8.7	23.3	0.064	<i>0.25</i>	<i>20271</i>	Pulsed injections of clay
	2	280, 230, 220	11.8	23.7	0.044	<i>0.22</i>	<i>27966</i>	Pulsed injections of clay
	3	810	8.6	23.6	0.064	<i>0.26</i>	<i>20296</i>	Pulsed injection of clay

Figure DR4: Comparison of flow conditions in experiments from this study to the phase diagram presented in Baas et al. (2009).

Approximate range of experiments in this study shown in the gray box. Note that their diagram is for flow depths from 0.13-0.16 m, and that some of our experiments are slightly above those depths. Baas et al. Figure 17.

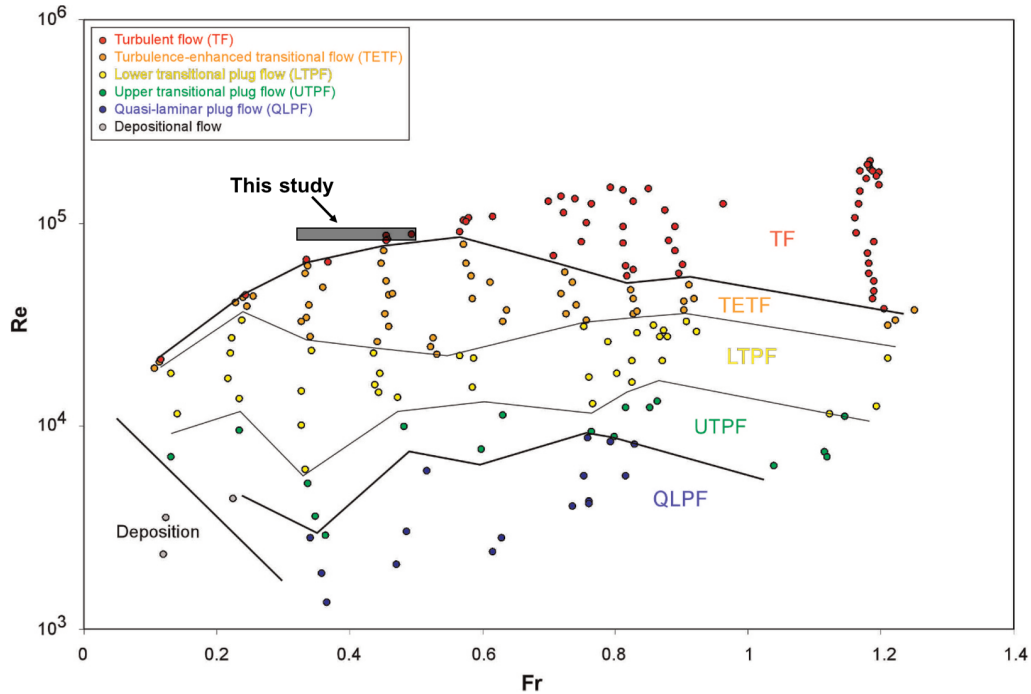


Figure DR5: Comparison of experiments in this study to the clay flow phase diagram of Baas et al. (2009).

Approximate range of experiments in this study is shown in the orange box. U is the depth-averaged flow velocity and C is the depth-average volume concentration of clay. Baas et al. Fig 15A.

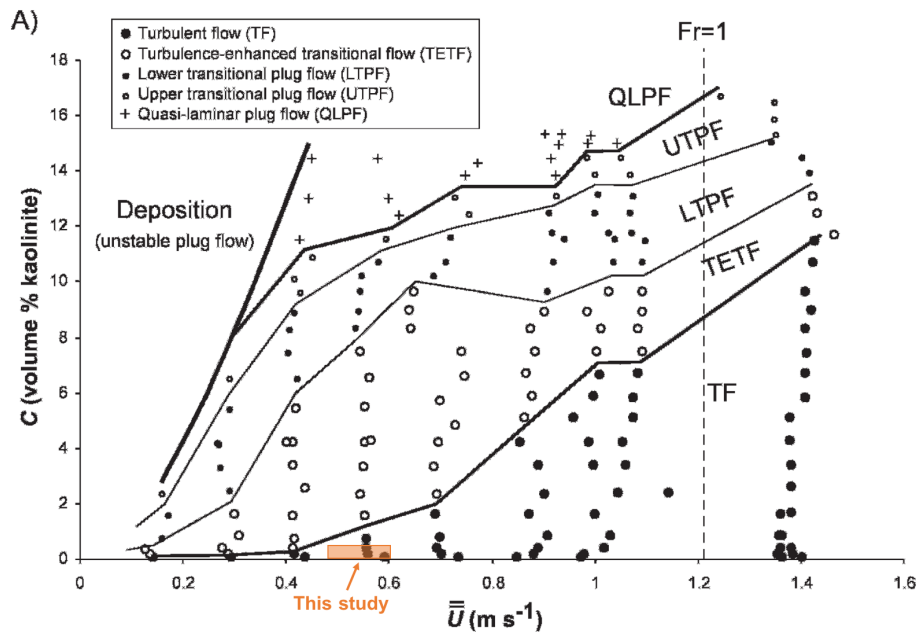


Figure DR6: Topographic profiles through time of each experiment.

The top figure in each set is the measured values and the bottom figure is smoothed profiles, which is accomplished with a moving window two average dune lengths (50cm); colors show profiles every 30 minutes (light to dark, as in Manuscript Figure 1). Vertical exaggeration is 3x.

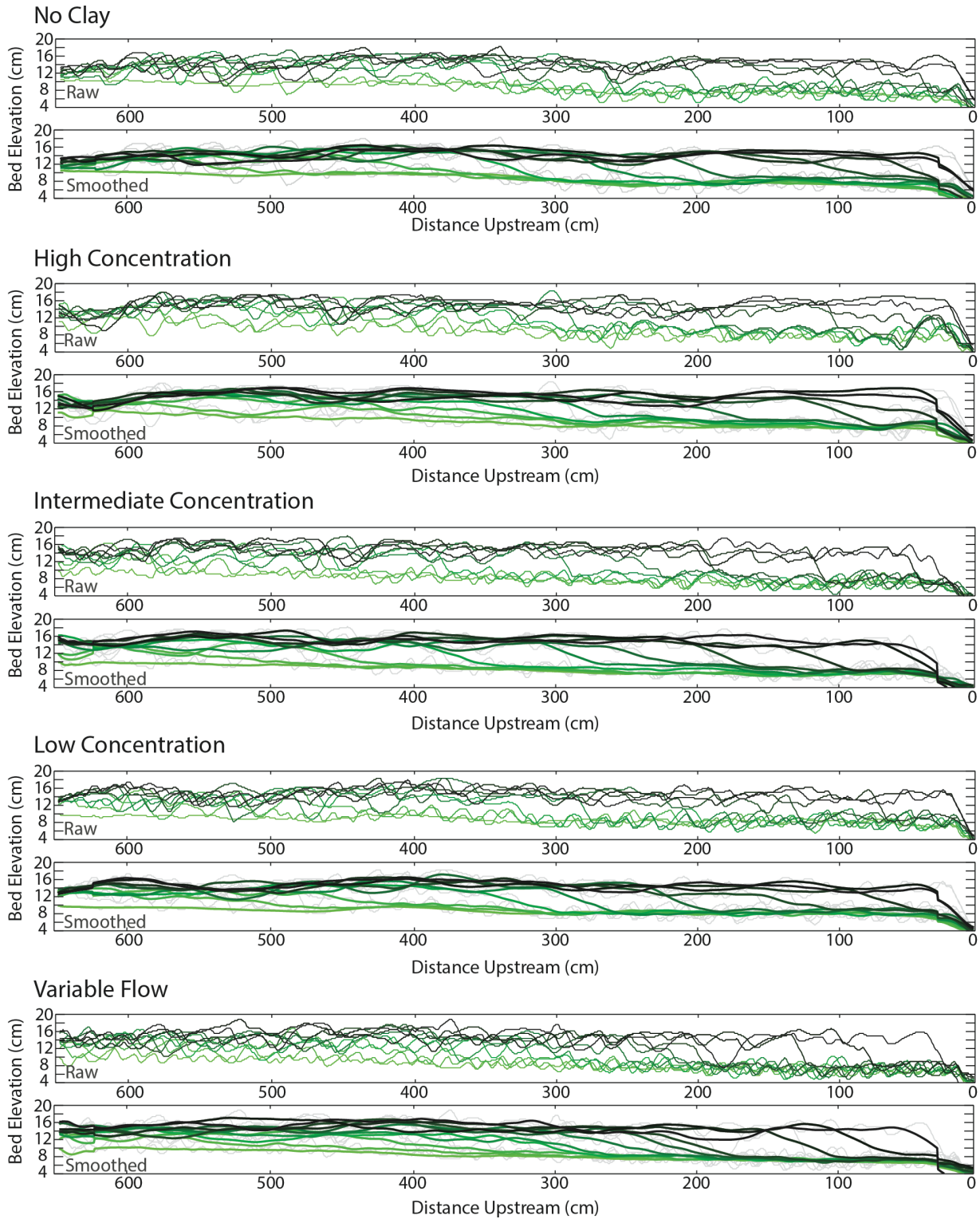
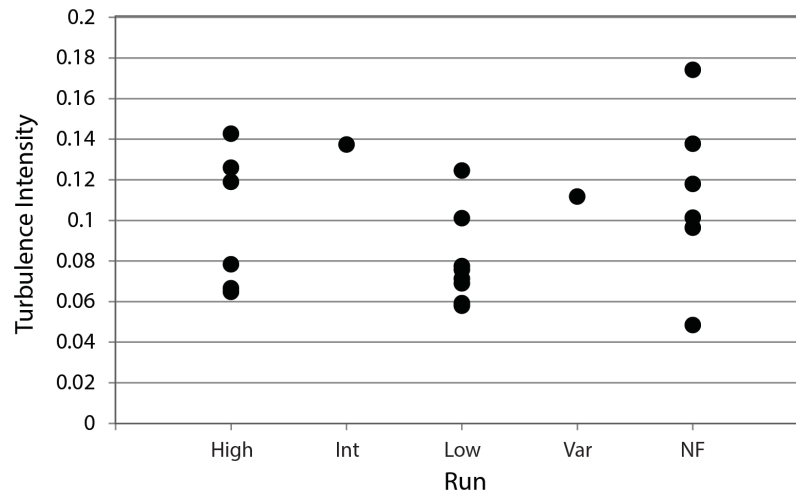


Figure DR7: Turbulence intensity calculated from ADV data from each run.
 There is no evidence of damping of turbulence at high clay concentration.



WinADV was used to process ADV data. Data were filtered using the automatic despiking program and used to calculate Turbulence Intensity (TI):
 Turbulence intensity (TI)

$$TI = \frac{u'}{U} = \frac{\sqrt{\frac{1}{3}(u_x'^2 + u_y'^2 + u_z'^2)}}{\sqrt{U_x^2 + U_y^2 + U_z^2}}$$

where u' is the root mean square of the turbulent velocity fluctuations and U is the mean velocity.

Figure DR8: Suspended sediment concentration profiles.

Experiments show a generally well-mixed clay concentration throughout the water column. Clay concentration varies during a run, but there was no overlap in clay concentration between runs.

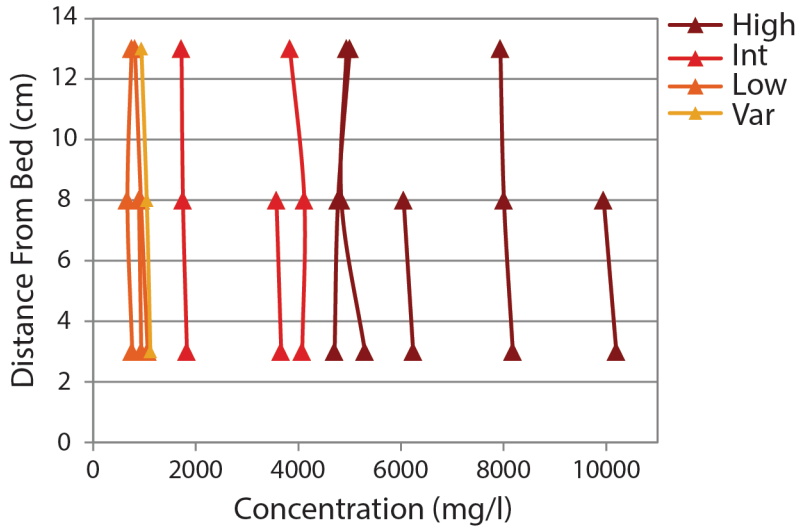
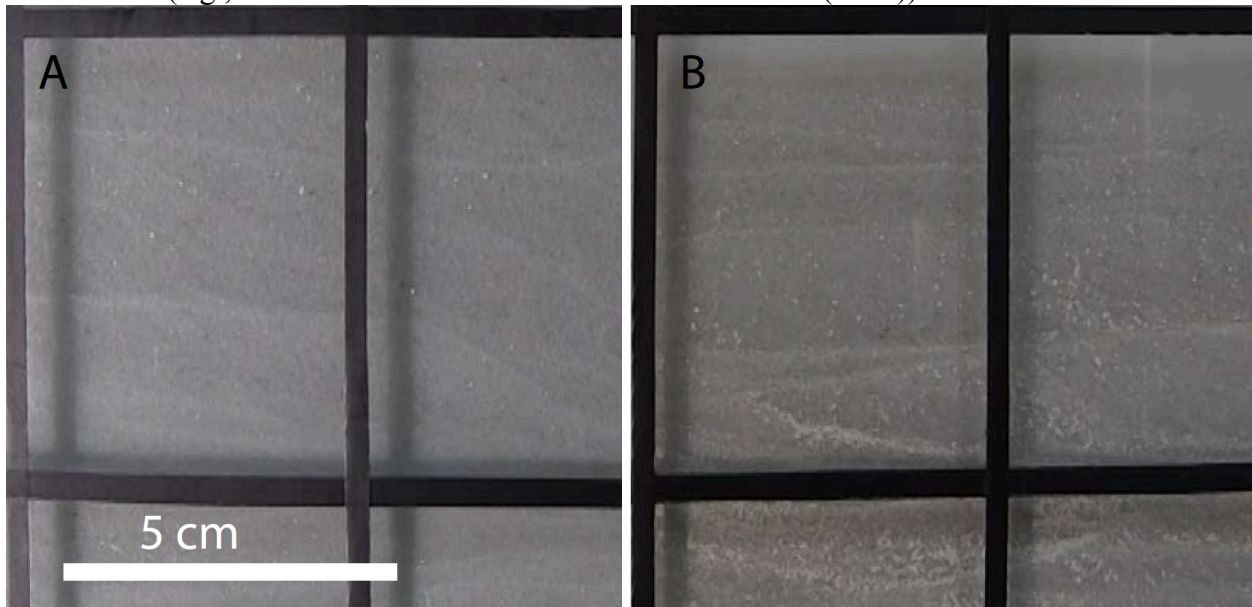


Figure DR9: Example images of clay aggregates in experimental runs.

Kaolinite flocs (white dots) in both the low-concentration run (A) and in the high-concentration run (B). Along the flume wall, in videos, there was evidence of flocculation in all runs, with more in the high-concentration experiment. However, clay flocculation was not did not occur at a level that changed the overall concentration of clay recorded in each experiment (Figure DR8), so it was not the dominant mode of clay transport in any of the runs. This is consistent with flocculation conditions documented in other experiments, where the conditions in this study (freshwater with clay concentrations <0.5 wt %) are below reported thresholds for significant flocculation (e.g., > 3.0 wt % in fresh water in Sutherland et al. (2015))



DEPOSIT CHARACTERISTICS AND CLAY ACCUMULATIONS:

Table DR4: Experimental deposit characteristics and clay-mapping results.

<i>Run description</i>	No Fines	Low Concentration	Intermediate Concentration	High Concentration	Variable Discharge
GENERAL DEPOSIT CHARACTERISTICS					
Aggradation phase deposit thickness (cm)	4.3	4.2	4.6	5.1	5.0
Bypass phase deposit thickness (cm)	3.0	2.6	3.5	3.0	3.2
Total deposit cross-sectional area (cm²)	4313	4533	4627	4737	5230
Aggradation phase deposit cross-sectional area (cm²)	2549	2554	2596	3022	3250
Bypass phase deposit cross-sectional area (cm²)	1765	1976	2032	1664	2010
Fraction of total deposit formed during aggradational phase	0.59	0.56	0.56	0.64	0.62
CLAY ACCUMULATIONS					
<i>Types of clay accumulations</i>	None	None (small drapes near weir downstream of test section)	Continuous clay drapes, abundant intercalated clay	Continuous clay drapes, clay-rich lenses, abundant intercalated clay	Discontinuous clay drapes
<i>Percent of total run deposit</i>					
Intercalated clay	N/A	0	34	40	0
Drapes	N/A	0.1	8	12	1
Clay rich lenses	N/A	0	0	6	0
<i>Percent of aggradation phase deposit</i>					
Intercalated clay (%)	N/A	0	61	62	0
Drapes (%)	N/A	0.1	14	19	1
Clay rich lenses (%)	N/A	0	0	10	0

BED DEPOSIT SAMPLING

After each experiment, the bed was slowly drained and allowed to dry for two days prior to excavation. At this point the bed was dry enough to excavate without significantly collapsing. Bed-deposit samples and photographs were taken from the middle of the flume at various locations at different depths (Table 3) in order to capture samples deposited during both bypass and aggradation phases. These samples were taken with a 7cm x 7cm excavator tool, which allowed for bulk sediment samples. Bed-deposit samples were then wet-sieved to determine the fraction of clay.

Table DR5: Bed-deposit sample locations and weight percent of clay in the sample.

Depositional phase and type of clay accumulations captured by each sample are noted. Qualitative sample descriptions describe the nature sample after being oven dried. Sands in some samples were clumped together and had to be manually disaggregated after sampling, indicating abundant clay. The NF run was a control experiment conducted with no clay discharge. Clay-sized material detected in that run came from the water (supplied from the Mississippi River via the St. Anthony Falls Lab main-channel diversion) or residuum within the sand supply.

Sample number	Run	Location (m)	Depth (cm)	Total weight (g)	Clay weight (g)	Clay %	Phase and clay types captured	Qualitative sample description
NF-1	NF	2.00	12.5-15.5	536.56	0.06	0.011	bypass	loose sand
NF-2	NF	2.00	9.5-12.5	523.92	0.08	0.015	aggradation	loose sand
NF-3	NF	5.00	12.0-15.0	491.25	0.07	0.014	bypass	loose sand
H-1	High	2.80	11.5-14.5	748.70	5.22	0.697	bypass	sticky/clumpy
H-2	High	2.80	8.5-11.5	825.56	16.87	2.044	aggradation. Clay drapes	hard
H-3	High	5.60	11.5-14.5	692.41	2.22	0.321	bypass	sticky/clumpy
H-4	High	5.60	8.5-11.5	778.64	2.46	0.316	bypass	sticky/clumpy
H-5	High	1.70	7.0-10.0	787.79	33.37	4.236	aggradation. Part of clay rich lens	hard
I-1	Int	3.35	11.5-14.5	716.00	1.50	0.210	bypass	loose with clumps
I-2	Int	3.35	8.0-11.0	833.63	3.47	0.416	split	sticky/clumpy
I-3	Int	2.35	11.0-14.0	783.41	2.25	0.288	bypass	loose with clumps
I-4	Int	2.35	7.0-10.0	859.58	15.58	1.813	aggradation. Clay drapes	hard
I-5	Int	4.60	12.5-15.5	700.41	1.46	0.209	bypass	loose with clumps
I-6	Int	4.60	8.5-11.5	901.94	1.97	0.218	split	loose with clumps
L-1	Low	1.80	11.0-14.0	746.79	0.35	0.047	bypass	loose sand
L-2	Low	1.80	7.5-10.5	799.44	0.51	0.064	aggradation	loose sand
L-3	Low	4.10	11.0-14.0	824.75	0.38	0.046	bypass	loose sand
L-4	Low	5.50	11.0-14.0	419.72	0.23	0.055	split (mostly bypass)	loose sand
V-1	Var	3.70	11.5-14.5	717.34	0.43	0.060	bypass	loose sand
V-2	Var	3.70	8.0-11.0	871.74	2.00	0.229	aggradation. Part of clay drape	loose sand with clumps
V-3	Var	5.25	11.5-14.5	778.63	0.51	0.065	bypass	loose sand
V-4	Var	5.25	8.5-11.5	791.50	0.74	0.093	aggradation	loose sand
V-5	Var	2.00	7.5-10.5	896.84	1.74	0.380	aggradation. Part of clay drape	loose sand with clumps

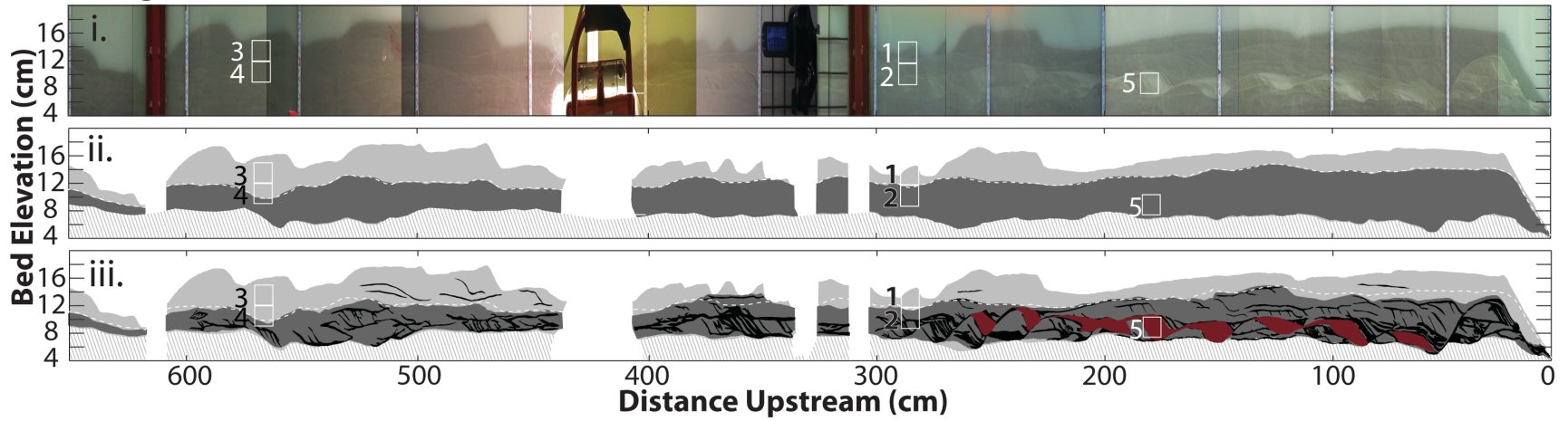
Bed Deposit Mapping Description and Images

Clay accumulations and bed areas are mapped on the vertically exaggerated images. Overlain topographic profiles and bed elevation points taken during the run helped determine which sediment was deposited during the bypass vs. aggradation phase. Clay accumulations were mapped on photographs of the bed. Clay accumulations appear whiter than the background sand, which is a tan color. Lighter colored sand indicates a higher abundance of intercalated clay (verified with weight percents of individual samples from these regions). Long and thin accumulations of clay were mapped as drapes and larger, thicker deposits were mapped as clay lenses. Bed areas of each type of clay accumulation were quantified using image analysis tools in Matlab.

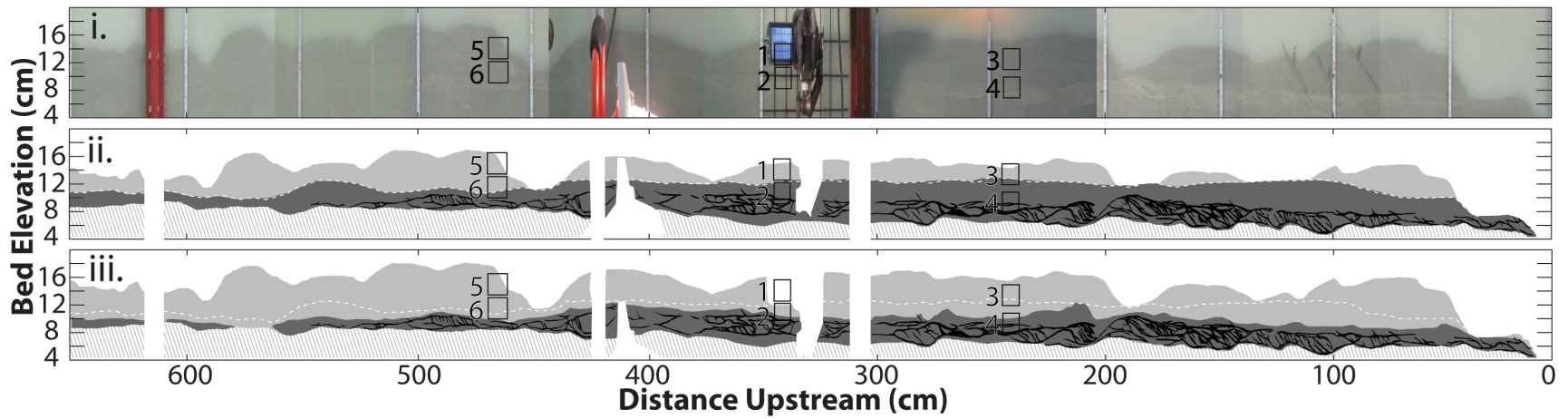
Figure DR10: Photographs and mapped clay accumulations of each run as seen through the glass wall of the flume.

(Next pages) Vertical exaggeration is 3x. The y-axis is depth in centimeters. Hatched area is pre-run sediment. White areas are obstructed views of the bed. Sample locations are noted by black boxes. Each experiment (A-D) includes the following: i) composite photograph of test section through glass panel, ii) map of clay accumulations preserved in the bed (black) and definition of aggradational phase area (dark gray) and bypass phase area (light gray), and iii) map of different types of clay accumulations observable in the bed including, intercalated clay (dark gray), clay drapes (black), and clay rich lenses (red).

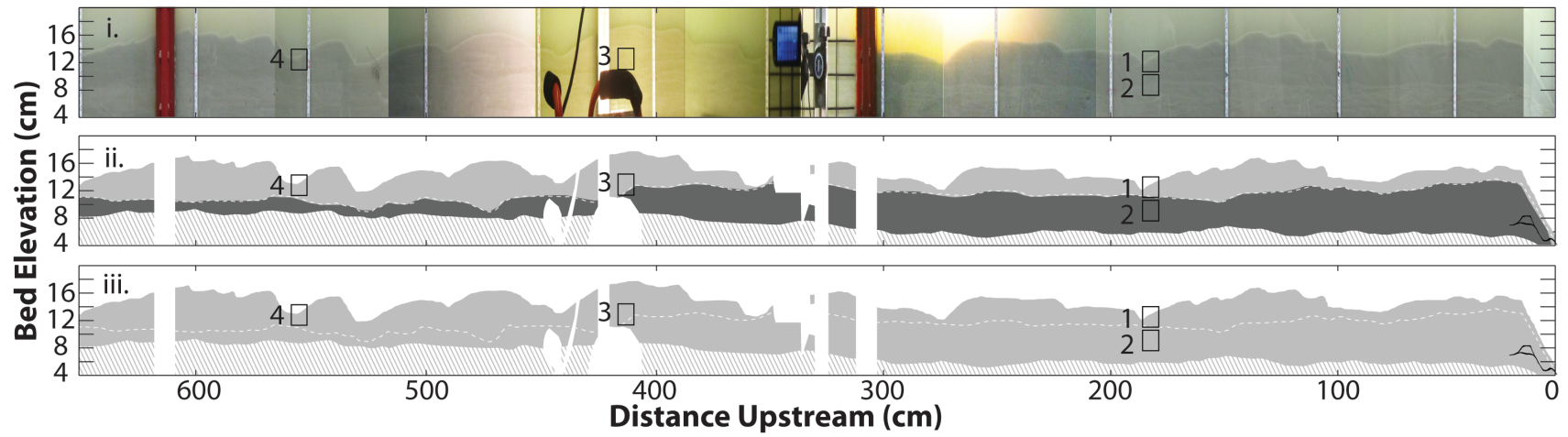
A. High Concentration Run



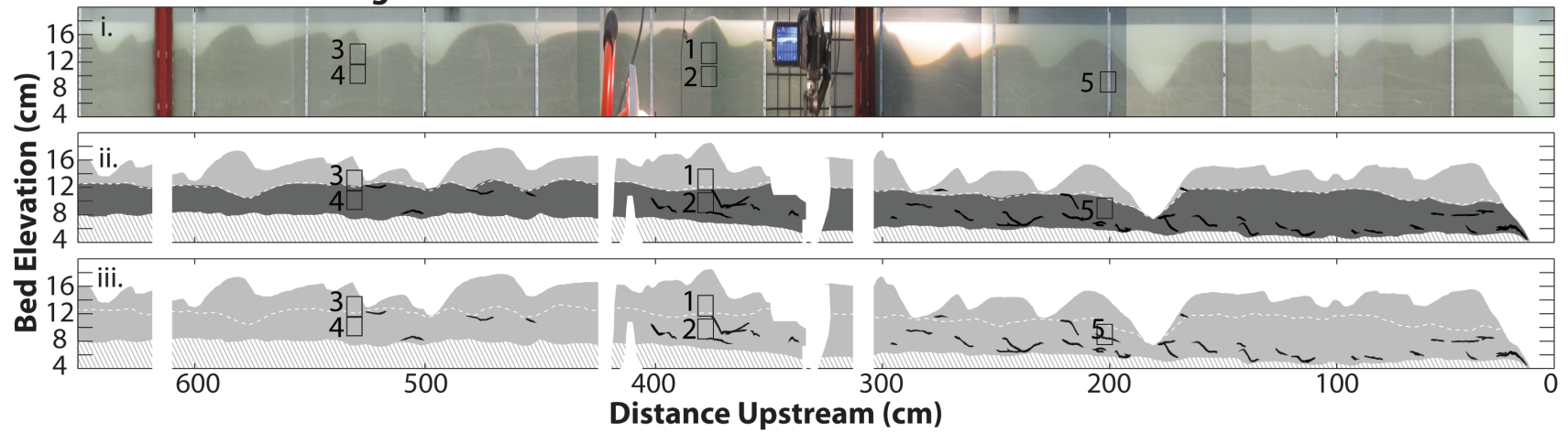
B. Intermediate Concentration Run



C. Low Concentration Run



D. Variable Discharge Run



REFERENCES

- Baas, J. H., Best, J. L., and Peakall, J., 2011, Depositional processes, bedform development and hybrid bed formation in rapidly decelerated cohesive (mud-sand) sediment flows: *Sedimentology*, v. 58, p. 1953-1987.
- Baas, J. H., Best, J. L., Peakall, J., and Wang, M., 2009, A phase diagram for turbulent, transitional, and laminar clay suspension flows: *Journal of Sedimentary Research*, v. 79, p. 162-183.
- Packman, A. I., and MacKay, J. S., 2003, Interplay of stream-subsurface exchange, clay particle deposition, and streambed evolution: *Water Resources Research*, v. 39, no. 4.
- Sutherland, B. R., Barrett, K. J., and Gingras, M. K., 2015, Clay settling in fresh and salt water: *Environmental Fluid Mechanics*, v. 15, no. 1, p. 147-160.
- Wilkerson, G. V., and Parker, G., 2011, Physical basis for quasi-universal relationships describing bankfull hydraulic geometry of sand-bed rivers: *Journal of Hydraulic Engineering*, v. 137, no. 7, p. 739-753.