Data repository and supplemental information for Wysocki and Hajek: Mud in sandy riverbed deposits as a proxy for ancient fine-sediment supply

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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 (21 g/L slurry for the Low Concentration and Intermittent Discharge runs, 85 g/L slurry for the Mid-concentration run, and ~179 g/L slurry for the High Concentration run), 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 sample 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

Intermittent Discharge Run:

<https://www.youtube.com/watch?v=N4nBBHzqulE>

<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	Intermittent Discharge
EXPERIMENTAL CONDITIONS					
Water discharge (l/s)	21	21	21	21	21 with pauses of 0 (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 Intermittent Discharge run

	Part 1	Part 2	Part 3	Part 4	Part 5
Run time (min)	59	55	56	66	27
Settling time (water discharge = 0; 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 = Intermittent Discharge 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, Intermittent Discharge (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:

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

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 been easily suspended and not settled within the length of the flume. Given the slowest average water velocity 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)). The potential role of fine-sediment transport via flocculated or aggregated particles in these experiments is discussed in Figures DR9 and DR10.

Comparison with other experimental studies

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	
	Low Conc.	1000	16.6	50	0.0019	0.39	83000	Variable Flow Run values are for high flow conditions
	Intermed. Conc.	4000	15.1	40	0.0016	0.33	60400	
	High Conc.	8500	14.9	60	0.0019	0.50	89400	
	Intermittent 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	0.25	20271	Pulsed injections of clay
	2	280, 230, 220	11.8	23.7	0.044	0.22	27966	Pulsed injections of clay
	3	810	8.6	23.6	0.064	0.26	20296	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. Variable Flow refers to the Intermittent Discharge experiment.

Figure DR7: Turbulence intensity calculated from ADV data from each run

There is no evidence of damping of turbulence at high clay concentration. (High = high concentration, Int = intermediate concentration, Low = low concentration, Var = intermittent discharge, NF = no fines control run.)

WinADV was used to process ADV data. Data were filtered using the automatic despiking program and used to calculate 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 (following, e.g., Bridge and Demicco, 2008).

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. (High = high concentration, Int = intermediate concentration, Low = low concentration, Var = intermittent discharge.)

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. Flocculation may have created a clay bed-material load by generating particles large enough to behave like sand. The constant clay-concentration profiles with depth (Figure DR8) contrast with the expected increase in clay concentration with depth if the majority of fine sediment were being transported as larger aggregates (Lamb et al., 2020). Clay concentrations in the flume (freshwater with clay concentrations <0.5 wt %) were below thresholds for significant flocculation documented in other experiments (e.g., > 3.0 wt % in still, fresh water in Sutherland et al. (2015)). However, concentrations in the mixing tank used to introduce clay to the flume were much higher and could have produced clay flocs and introduced them to the flume.

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 collapsing. Bed-deposit samples and photographs were taken from the middle of the flume at various locations at different depths (Table DR4 and Figure DR10) 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 in a manner analogous to hand-sample collection of bed-material deposits from ancient outcrops. Bed-deposit samples were then wet-sieved to determine the fraction of clay.

Table DR4: 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. (Var = intermittent flow)

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

Expected clay weight percent in bed deposits

The expected weight percent of clay in the bed ($E_{wt\%clay}$; Table in the main manuscript) is the percent mass of interstitial clay that could be present in bed pore space given the supplied clay concentration in the flow (C_{clay}), bed porosity (f_{pore} ; assumed to be 0.35 after Beard and Weyl (1973), and density of sand ($\rho_{quartz} = 2.65 \text{ g/cm}^3$).

$$E_{wt\%clay} = \left(\frac{C_{clay} f_{pore}}{C_{clay} f_{pore} + \rho_{quartz} (1 - f_{pore})} \right) \times 100$$

Figure DR10: Comparison with Lamb et al. (2020) & de Leeuw et al. (2020)

Experimental results from this study compared with modern river data from Lamb et al. (2020) and de Leeuw et al. (2020). Lamb et al./de Leeuw et al. data tables were filtered for rivers with fine sediment (<16.5 micron, approximating the coarse tail of the kaolin clay supplied in these experiments) reported in both bed and suspended-sediment samples (Ganges and Yellow rivers). Mass fraction in bed is the total mass reported of particles <16.5 micron in bed samples. Mud suspended sediment volume concentration is the average overall suspended sediment concentration weighted for the fraction of suspended sediment that is <16.5 microns. Wysocki and Hajek experimental values show the average suspended sediment concentration supplied to the experimental runs and the average bed mass fraction found in bed-deposits samples from both the aggradation and bypass phases of the experiments. Available modern river data show the same overall trend of increasing mud in the bed for higher suspended-sediment concentrations. Expected weight percent of clay $E_{wt\%clay}$ is estimated as shown in the preceding section.

reworking period could allow significant fine sediment to accumulate in bed deposits for a range of effective grain sizes.

Potential fine sediment yield from settling is normalized by the expected mass of pore filling-fines (see **Expected clay weight percent in bed deposits**, above) for the low-concentration run (1000g/mL). Potentially settled fines were estimated as the amount of fine sediment that could settle on a 1 mm² patch of bed over a given time period (Settling time), given a settling velocity determined by an effective grain size (assuming density = 2.65 g/cm³). Maximum values are limited by experimental flow depths of 15 cm (i.e. if settling velocity would be high enough to exceed 15 cm for a given settling time, the potential amount of fines settling in a 15 cm water column was assumed).

Bed reworking period, the average time between successive bedform scours passing a given location, is estimated as 10.8 mins (648 sec) for the aggradational phase and 1.3 mins (78 sec) of the experiments. (Bedform lengths in the experiments were ~14 cm and average bedform-migration rate was 1.3 cm/min for the aggradational phase and 10.5 cm/min for the bypass phase of the experiments; see Table DR1.)

DEPOSIT CHARACTERISTICS AND CLAY ACCUMULATIONS

Table DR5: 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

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 percent results 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 DR12: 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. The depth and downstream locations of samples (collected from the center of the flume, not along the flume walls) 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

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