PRELIMINARY EXPERIMENTS REGARDING THE EFFECT OF FROZEN SEDIMENT ON FLUVIAL MORPHOLOGY.
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Introduction: The development of high-sinuosity meandering rivers on Earth has been linked to the increased cohesion provided by the rise of vascular plants during the Silurian [1]. However, several locations on Earth [2,3] and Mars [2,4,5,6] provide examples of high sinuosity apparently in the absence of vegetation. Hypotheses for the origin of such morphology include cohesion from clays, salts, and ice [2]. Whereas recent laboratory studies have tested the influence of small sprouts on model rivers in flumes [7], we explore the influence of a frozen substrate on meandering in a small flume. Here, we use the novel Freezable Flume for Understanding Meandering Experimentally (FFLUME; **Fig. 1**) to investigate the evolution of permafrost rivers through small-scale physical models.

Several changes in river morphology can be expected due to the enhanced cohesion provided by frozen sediment rather than damp room-temperature sediment. We test how frozen substrate effects undercutting, width-to-depth ratios, sinuosity, and sediment flux. Measurements necessary for these tests are taken at regular interval for a total of 10 trials (5 warm, 5 icy) keeping constant discharge, slope, sediment properties, and initial channel morphology—varying only temperature.

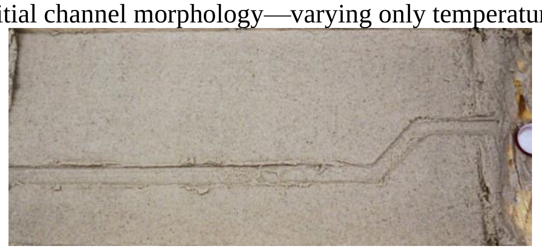

Figure 1. FFLUME viewed from above with leveled sediment and initial channel.

Methods: *Flume design.* FFLUME is a 132×54.6 cm stream table. Its relatively small size enables it to fit within a commercial chest freezer to bring the temperature of the substrate down to -20 °C. Experiments were performed in a room temperature lab, with FFLUME resting on a larger Little River Research & Design stream table. FFLUME was constructed of lumber with a layer of plastic sheeting to protect the wood. Water is pumped into the upstream end of the table and injected into a small cup to dampen velocity and allow for a natural flow. The downstream end of FFLUME is open to allow for free flow onto the larger stream table below, upon which transported sediment is deposited on another plastic sheet for later weighing.

Experiments used ~35 kg commercial play sand that was washed to remove the finest clay particles. The resulting grain size was predominately coarse sand (~0.5 mm). Viewed under a microscope, the sand was determined to be ~97% quartz, with some darker grains.

Experimental procedure. Each experimental run began by leveling a ~2.5-cm-thick layer of damp sand within FFLUME. At the upstream inflow, a small (~20×8 cm) cavity was left for inflowing water to pool. A template was used to create an initial channel ~1-cm-deep and 4-cm-wide with two 45° bends to give an initial sinuosity of ~1.03. The entire apparatus was tilted to a 1° slope (steep compared to natural systems <0.5°). Experiments ended when meanders propagated to the sidewalls of FFLUME and experienced edge effects.

A camera positioned above the stream table captured near-perpendicular images/video. Discharge was set to be sufficiently fast for entrainment and measured at the inflow tubes to be ~50 ml/s. Plastic particles periodically released into the flow indicated surface velocities as high as ~35 cm/s. After numerous trials with different conditions, five runs were performed with room temperature sediment and five runs with frozen sediment. Frozen sediment was prepared under the same procedure as the room temperature sediment, then placed overnight in a -20 °C chest freezer. Simultaneously, 35 gallons of water was cooled to 4 °C overnight in a walk-in fridge.

Cooled water was circulated and measured for temperature every ~5 minutes during frozen experiments. For most frozen trials, temperatures began ~4 °C and increased at a rate of ~0.04 °C/min during the duration of the 1–2 hour trials. The final, coldest run was aided by the addition of 20 lbs of ice to reach an initial temperature of ~1 °C. Thermal imaging during one run indicated relatively spatially constant temperature across the frozen sediment surface and cooling of circulating water with distance downstream.

Results: *Channel shape.* The initial 4×1 cm channel cross-section rapidly increased in W/D ratio. Channel width increased more rapidly for room temperature experiments than for frozen experiments and was overall greater than for frozen experiments over the same time (**Fig. 2A**). In both conditions, channel widths increased by 3- to 4-fold. Significant undercutting occurred in frozen experiments as the surface layer of frozen sediment remained strong, overhanging by several cm before collapsing, melting and weathering away.

Channel morphology. With an initial bend (~0.25 wavelength), meanders developed downstream such that ~1.5 wavelengths fit in the length of the apparatus. With relatively slow upstream flow speeds, the initial bend experienced little/no evolution while the downstream meander bends gradually propagated downstream and laterally for the duration of the experiment.

Channel sinuosity for unfrozen sediment increased with less variability than for frozen sediment, overlapping the highest sinuosity frozen experiments (**Fig. 2B**). That is, the most rapidly migrating frozen channels evolved at a rate less than or equal to that of the unfrozen channels. There was high variability in the sinuosity trends of frozen experiments at long runtimes not reachable in the rapidly migrating room temperature runs.

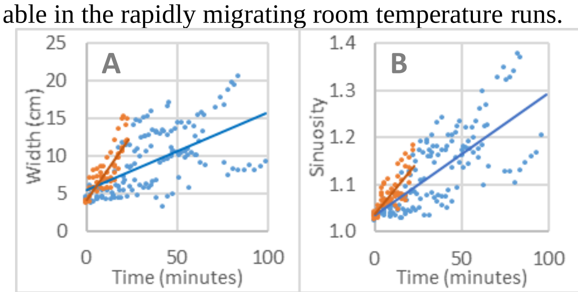

Figure 2. Preliminary data for channel (A) width and (B) sinuosity through time for frozen (blue) and room temperature (orange) experiments.

Sediment transport. The majority of sediment transport occurred at the downstream end of the channel as headward erosion increased the channel bed slope to >1.5°. Little/no sediment transport occurred before the first bend, where flow rate was slowest. Sediment was dominantly eroded at the outside of bends and dominantly deposited at the inside as point bars or else carried completely out of the apparatus. Chute cutoffs commonly formed across the point bars but only diverted a small portion of the flow.

The sediment flux through FFLUME in terms of mass averaged over the timespan of the run suggests significantly lower transport rates in frozen experiments (~0.5 g/s) compared to unfrozen (~2 g/s). This result can be expected due to the extreme undercutting of the frozen rivers, leaving much surface sediment untouched.

Discussion: The overall slower evolution of sinuosity under frozen conditions suggests permafrost may be an unlikely contribution to the formation of meandering rivers in the absence of vegetation. Channel cross sections were generally narrower with frozen sediment than with warm sediment during the first 20 minutes, likely due to prolonged undercutting that led to underestimated widths until bank collapse.

Given the warmer temperature of the circulating water (~5 °C) compared to the substrate (-20 °C), erosion occurred partly due to melting. Despite differences in water temperatures of a few degrees between frozen experiments, there was no apparent trend with resulting morphology—suggesting a limited role for melting.

With gradual warming of the frozen substrate by interaction with the chilled water and ambient air, entrained quartz grains can be expected to lose cohesion permanently. Whereas transported clays can redeposit on banks and add to cohesion further downstream, sediment loosened from frozen banks transported in the same manner as room temperature alluvium. However, a few cases of apparent refreezing of water along the frozen banks of channels permit the possibility for sustained cohesion in permafrost environments.

Acknowledging caveats, rough comparisons can be made to natural rivers. Whereas many meandering permafrost rivers in the arctic cannot be isolated from the influence of vegetation [2], at least one example in the McMurdo Dry Valleys of Antarctica, the Onyx River, demonstrates high sinuosity [8]. Channels in FFLUME steadily increased in sinuosity up to ~1.4, and may have continued if given more lateral space. As a comparison, a ~1 km meandering section of the Onyx River shown in LIDAR in [8] exhibits a sinuosity of ~1.35, suggesting frozen ground may be sufficient for such meandering. Still, such sinuosity measurements are dwarfed by that of many ancient fluvial deposits on Mars (up to S~1.5-2.3, [2]) as well as the warm, clay- and salt-rich Quinn River (S~1.8, [2]). Further study of the Onyx River with LIDAR in comparison to similar warm meandering rivers like the Quinn may prove to be good analogs for the present experiments and possibly ancient rivers on Mars [e.g., 2,4,5,6].

Conclusions: Various hypotheses have been proposed for the onset of meandering rivers, but few have been tested in a laboratory setting. Cohesion of sediment necessary for lateral migration may be provided in permafrost conditions, but examples on Earth without vegetation are exceedingly rare. Experiments in FFLUME contrasted channel evolution under ambient conditions with that under frozen conditions. Measurements of channel shape, morphology, and sediment flux over the same timescale include generally slower lateral migration in frozen settings, suggesting that a frozen substrate is unlikely to enhance meandering under the tested conditions. Future experiments in a larger, more tightly constrained apparatus could provide enhanced realism.

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