Mud bedforms in a natural ice flume

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ABSTRACT

An ephemeral, ice-based flume developed in Medway Creek (London, Ontario) during a February thaw when water at ~1°C flowed over the ice surface forming a < 10 cm deep, ~ 3 m wide channel. Eroded muddy bank sediment, composed of silt to medium-sand sized aggregates, formed linear streamers that revealed streaks in the boundary layer. In water 6-8 cm deep with a flow velocity of ~ 8-12 cm/s, mud aggregates were molded into lunate, transverse, and ovoid ripples a few mm high. Clear water allowed mud aggregates in streamers to be observed accreting to, and migrating over mud ripples. Downstream of larger ripples, mud streamers were swept clear of the bed, perhaps due to vortices shed by the ripple. Where flow exceeded ~ 12 cm/s, mud ripples were gradually replaced by mud aggregate streamers which in turn were washed out in an area of faster (undetermined rate) flow. The flow conditions and bedforms in this ephemeral, natural flume are closely comparable to those described from laboratory flumes at 25°C; however the increased viscosity of water at 1°C may alter the stability field of mud ripples.

A NATURAL FLUME

For about 90 minutes, from about 9:00 on February 20th, 2016, a natural ice flume existed in Medway Creek (London, Ontario, Canada; 43°00′ 35.12″N, 81°17″ 41.18″W), because a thaw caused water level to rise and partially flood the ice on the surface of the creek. Mud aggregates were eroded from melting alluvial sediment that formed the stream bank. This unconsolidated alluvium was probably derived from Late Wisconsinan (approx 14 -13 ka; Barnett, 1992) glacial diamictites and glacio-lacustrine deposits exposed in the walls of the Medway valley (Fig. 1).

When the wholly impromptu observations were made, the flooded portion of the ice surface formed a shallow trough, 3-4 m wide, in which water depth increased from ~ 6 cm close to the bank to ~ 8 cm about 1 m farther out, reaching a maximum of about 10 cm before gradually shallowing to nil towards the center of the creek where the ice surface bowed up (Fig. 1). Mud aggregates eroded from the bank were carried across the smooth surface of the ice where they were moulded into ripples and streamers (Fig. 1).

Although no tape measure was to hand, a metre stick was fashioned from a straight plant stem and measured using the cm scale engraved on a Swiss Army Knife. Another plant stem served as a dipstick to measure water depth. The passage of floating plant debris parallel to the 1 m scale was timed using the second hand of a watch. Closer to the bank, in ~ 6 cm of water, debris took ~13 sec. to travel 1 m (or ~ 8 cm/s), whereas about 1 m further out, in ~ 8 cm of water, debris took ~8 sec. to travel 1 m (or ~12 cm/s; Fig. 2). The water temperature was ~1° C measured with a small skiing thermometer. Mud aggregates were estimated by eye to move at 5 to 10 mm/s on the bed.

Simplifying the dimensions to a channel 3 m wide x 0.08 m deep, water density 1000 kg/m^3 and dynamic viscosity at 1°C of 0.00173 Ns/m^2, yields a Reynolds number of ~3,470 for flow at 8 cm/s and ~5,200 for flow at 12 cm/s. Corresponding Froude numbers are 0.104 for 6 cm depth x 8 cm/s flow and 0.306 for 8 cm depth x 12 cm/s. The ice was deemed too thin to walk on safely, so observations and photographs were made leaning out from the bank, clinging to trees. By about 10:30 am, continued warming caused both water level and flow velocity to rise markedly, causing all the mud ripples to be swept from the surface of the ice. The muddy sediment forming the bank material (Fig. 1B), was sampled at a later date.

RIPPLES

In the most bank-proximal part of the ice flume, ripples did not develop (Fig. 3). Broadly lunate, transverse to ovoid mud ripples, estimated to be 1-4 mm high, developed a little further from the bank

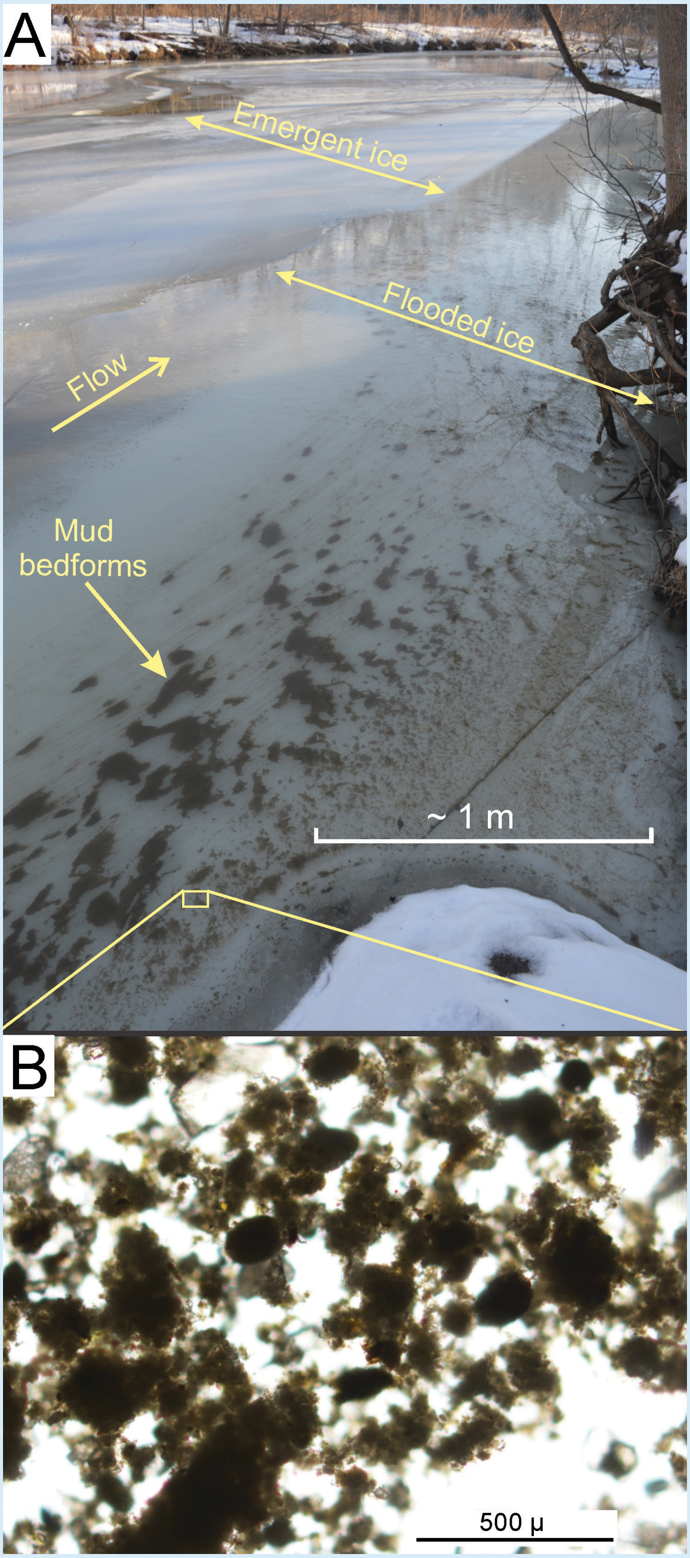

Figure 1: A. Overview of the ice flume looking downstream. The flooded portion of the ice varied between 3-4 m wide and was up to ~10 cm deep.
B. Transmitted light micrograph of a freshwater suspension of muddy bed material, comprising a mixture of loose aggregates of clay minerals, organic matter, and siliceous mineral grains (the latter largely out of focus below the mud aggregates). The sample was collected after the ice flume had melted, but at the same place that mud was being eroded on the day the mud ripples were observed.

in a region where water was 5-8 cm deep and flow was about 8 to 12 cm/sec (Figs. 2, 3). Even farther from the bank, where flow was > ~12 cm/s, ripples became smaller and changed from lunate to ovoid in a region transitional to slightly faster flow, which was dominated by near-parallel mud streamers that revealed the presence of streamwise vortices in the viscous sublayer (Allen, 1985; Figs. 3, 4, video S-1). Vortices inferred to be shed from the crests of the mud ripples appeared to 'sweep' the region downstream clear of mud streamers (Fig. 4A).

Because the sediment concentration was very low, the water clear, and the ice substrate white, it was easy to see the bedload of mud aggregates moving as discrete, non-cohesive particles over the ice surface. Aggregates consist mainly of very loosely-packed clay particles and range in size from silt to medium sand (Fig. 1B). Mud aggregates, moving in streamers, could be seen accreting to the stoss side of mud ripples. Close observation (see video recording, S-1) showed that mud aggregates migrated right over the ripples and then continued to travel downstream beyond the lee face, forming new streamers.

COMPARISON WITH A LABORATORY FLUME

Although the flow conditions and bedforms observed in this serendipitous natural flume could not be documented with the accuracy of those made in a laboratory flume, they do provide some comparative and corroborative information on the development of mud ripples in water at ~1°C, where dynamic vicosity is higher than in laboratory flume runs (cf. Schieber et al. 2007; Schieber and Southard 2009; Schieber and Yawar, 2009; Schieber, 2011), which were conducted with water at 25°C (e.g. 0.00173 Ns/m^2 vs. 0.00089 Ns/m^2). Schieber et al. (2007) observed that for a low sediment concentration of 0.03 g/l, the critical velocity for sedimentation was about 10 cm/s, rising to at least 26 cm/s for concentrations of 1 to 2g/l. In the ice flume, the suspended sediment concentration could not be measured, but appeared to be low. In consequence, water clarity, and visibility of bedforms, was excellent (in contrast to the high turbidity "sedimentology of milk" that prevails in experimental settings; Schieber, 2011), and also hinders observation in nature (Shchepetkina et al. 2018). The best-developed ripples, interspersed with mud streamers, formed in water flowing at about 8-12 cm/s. Southard and Schieber (2009) documented the passage of discrete mud (kaolinite)

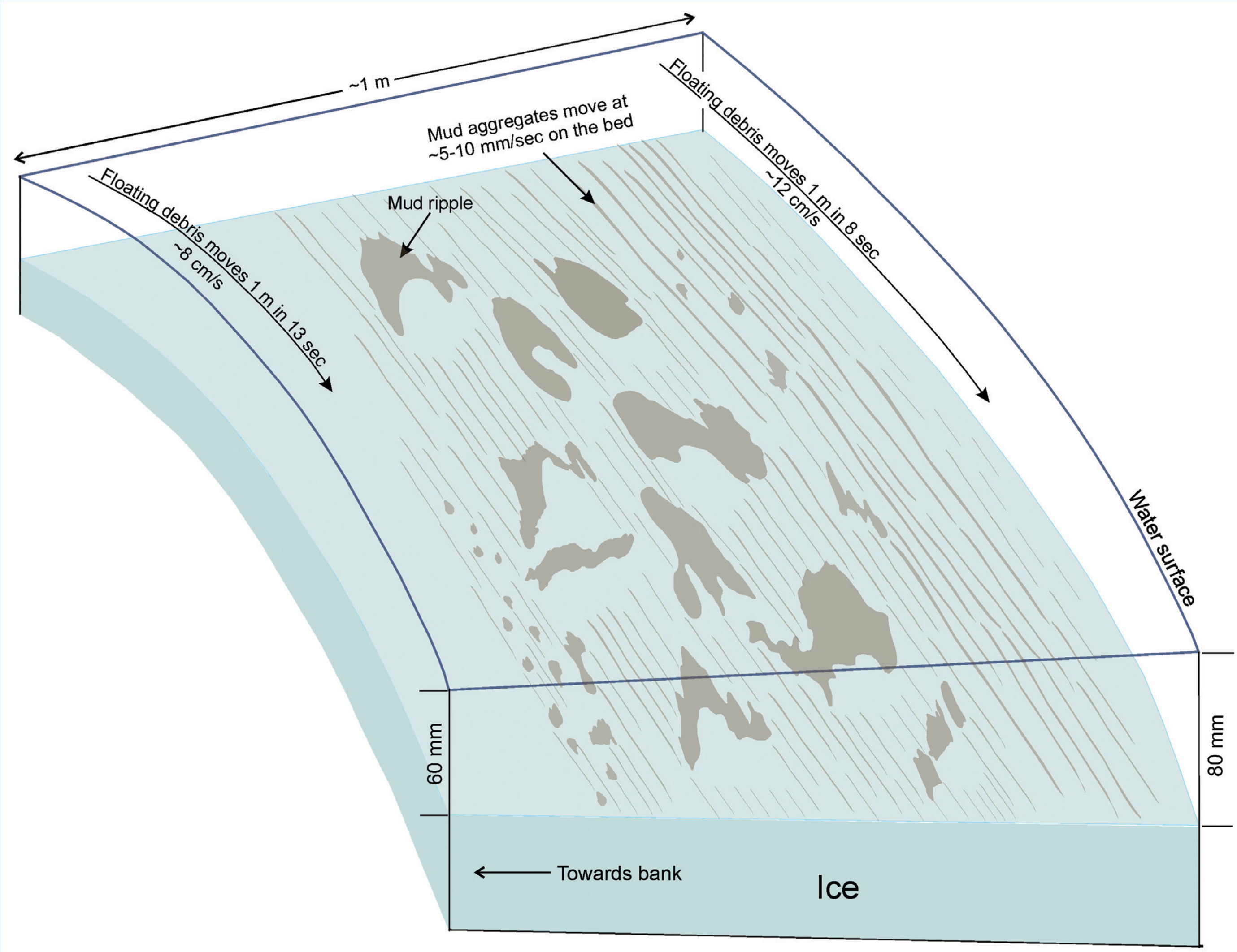

Figure 2: Diagram summarizing the water depth, flow velocity and distribution of mud ripples and mud streamers across the near-bank, accessible portion of the ice flume.

floccules over ripples, and their accumulation to form cross-lamination, exactly analogous to those formed in sand ripples. They also observed that mud particles avalanched episodically down the lee faces of ripples before being swept off in the flow. Although it was not possible to observe ripples very closely in the ice flume, examination of the video (S-1) taken looking obliquely down, shows that darker 'slugs' of mud slowly detach from the lee side of some ripples and are then abruptly swept off into the flow. It is possible that this is a manifestation of the episodic avalanching of mud aggregates. Schieber and Southard (2009) did not discuss the 'sweeping' of mud streamers from the region immediately downstream of ripples (Fig. 4A). This phenomenon may not have been observed due to a lack of contrast between streamers and a mud bed, as opposed to an ice bed.

Overall, both the flow conditions and mud bedforms observed in this natural ice flume appear to be comparable to those documented by Schieber et al. (2007) and Schieber and Southard (2009) under laboratory conditions. The increase in the viscosity of water with decreasing temperature would cause an increase in critical shear velocity (cf. Krögel and Flemming, 1998). It is possible that in cold water, mud ripples may form at a lower flow velocity than the ~10 to 26 cm/s range limit observed in the 25°C flume runs. The ice flume illustrates that both ripples and mud streamers can form and migrate at a flow velocity of about 8 cm/s, and perhaps slightly slower still. Cold water conditions may be the norm in some natural areas, such as the deep sea, and in nearshore areas subject to cold winter conditions (e.g. Shchepetkina et al. 2018). Experimental sedimentologists might consider introducing a chiller in flume experiments to further explore bedform development in cold-water environments!

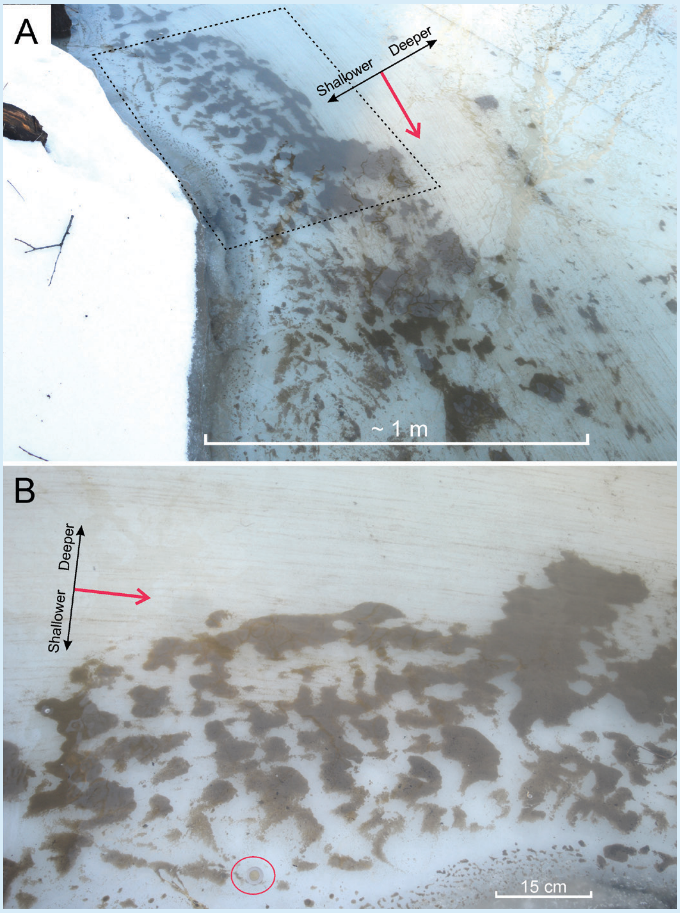

Figure 3: A. View upstream showing concentration of mud ripples in the near-bank portion of the flume, giving way laterally to long parallel mud streamers in slightly faster-flowing water in the center of the flume. Broken line outlines area of image in B.
B. Detail of rather irregular mud ripples passing laterally into streamers of mud aggregates. Canadian two dollar coin (encircled) is 28 mm wide.

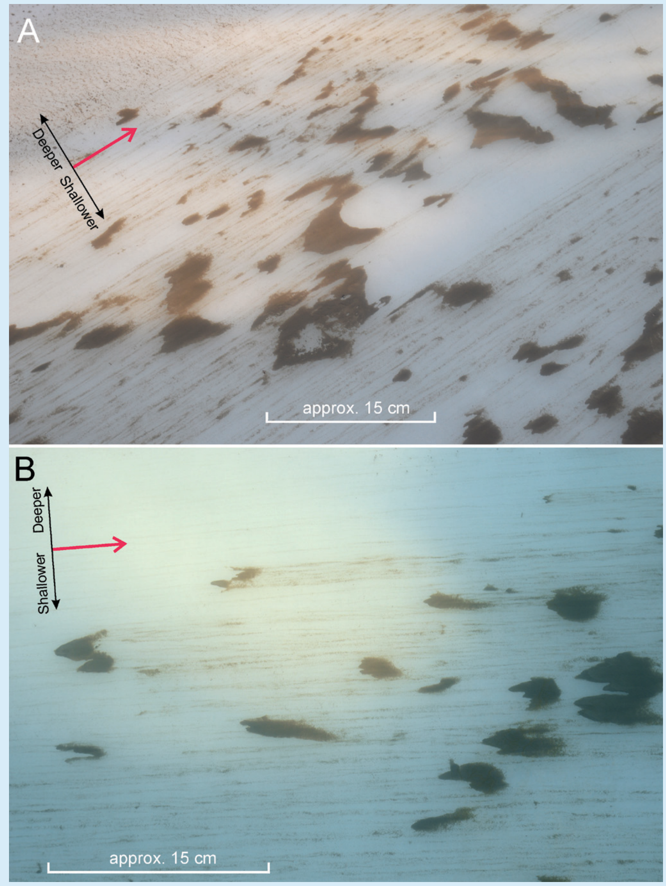

Figure 4: A. Detail of mud ripples showing lunate, transverse and ovoid planforms. It is postulated that vortices shed from the crests of the larger ripples were responsible for sweeping mud streamers from the region immediately downstream.
B. Detail of bank-distal portion of mud ripple field, showing small ovoid to lunate ripples, and their transition to an area dominated by mud streamers. The transition to streamers takes place where flow velocity appears to exceed about 12 cm/s.

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SUPPLEMENTARY DATA

S1. Video showing streamers of mud aggregates, and the episodic sweeping effect of flow streaks in the viscous sub-layer. Mud aggregates can be seen accreting to the stoss sides of ripples, and also migrating over the entire ripple. On some ripples, it is possible to see darker 'slugs' of mud slowly detach from the lee side, and then be abruptly swept off into the flow. This may be a manifestation of the episodic avalanching of mud aggregates. https://youtu.be/YkfEyXifv6c

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