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Discussions

Interactive comment on "Ribbed bedforms in palaeo-ice streams reveal shear margin positions, lobe shutdown and the interaction of meltwater drainage and ice velocity patterns" *by* Jean Vérité et al.

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Reply to the referee's comments: Martin Ross

We thank Martin Ross for their comments which have helped us to improve the manuscript. Replies to referee's comments are addressed below in red. Annotations (§1.) refer to the corrected manuscript paragraphs. Kind regards, Jean Vérité (on behalf of all co-authors)

Major comments

1. "It would be useful to provide more details about scaling and how exactly the analogue model is similar in terms of geometry and dynamics to the natural system. The authors simply refer to earlier studies, but I think it is important given this is still relatively new to clearly explain scaling in this case (i.e., ice lobe/stream, landforms)."

Our experimental device primarily involves water flow, within the bed and along the basal interface either channelized or distributed. This water flow controls both the silicon cap dynamics, responsible for bed deformation and sedimentary processes (erosion, transport and deposition). Thus, the scaling has to take into account the complex relation between silicon flow, water flow and subglacial landform development. As the experimental materials were selected in order to favour the reproduction of some key processes between the natural system and the experimental model (e.g. basal decoupling, bed erodibility and deformation) and to provide critical advantages lacking in the natural system (e.g. transparency to observe the interface and low viscosity of the cap to observe significant flow at the experiment timescale), some ratios of physical parameters (e.g. viscosity) are different, excluding a perfect scaling. However, as described in the section §3.1.1., Lelandais et al. (2016, 2018) proposed a scaling for a reduced-size version of our experiment model, considering the silicon lobe dynamic, the water flow and the subsilicon landform development. They demonstrate that the dimensionless ratio between the lobe margin velocity and the incision rate of subglacial erosional landforms has similar values in the model and in nature. In the same way, we demonstrate in this study that the dimensionless ratio between the ribbed bedform wavelength and the overlying cap thickness display compatible values in the model and in the nature (see §5.1.). Considering we aim to focus on relations between basal water flow, cap dynamic, bed erosion and deformation, we assume that these comparable dimensionless ratio between nature and experiments are satisfying. Furthermore, we now present in the new section §3.1.3. what the experimental device does not reproduce (e.g., shear heating, heat softening, melting, freezing, crevassing) and which elements are not scaled in the experimental device (e.g., shear margin width, channelized feature width).

2. “Why does it lead to a single lobe in one specific direction? I think an explanation about how the injection induces discrete deformation and movement along one specific direction in the silicon cap would be useful.”

In our experiments, the emergence of a system of fast-flowing stream and lobe is controlled by the growth and migration of a water pocket. The water pocket – whose formation results from the injection of water beneath the silicon – migrates toward the margin of the silicon cap following the pressure gradient. The pressure gradient is potentially influenced by the distance between the injection point and the silicon margin, small variations in bed permeability, variations in bed or silicon surface slopes. Although we aim to ensure a constant experimental protocol with almost identical input parameters, small variations in the above parameters can occur during experiment preparation. These variations will therefore control the pressure gradient and hence the migration path of water pocket and the formation of the silicon stream and lobe system. The specific direction of lobe development is mostly unpredictable.

3. “They do mention a few limitations later in the discussion (e.g. such as near line 555), but this should be more comprehensive and presented earlier. A full list of model simplifications and limitations, as well as assumptions for the comparison to natural phenomenon should be provided in the methods section. For instance, it seems the modelling ignores thermal effects.”

We agree that an exhaustive description of model physics, simplifications and limitations is necessary and we added a new section dedicated to this point in the revised manuscript (§3.1.3.). Furthermore, we complete the section dedicated to the discussion of experimental ribbed bedforms with their natural counterparts (§5.2.2.), notably regarding their formation processes. Those two sections thus present a comprehensive and clear discussion of what it is reproduced in the experimental model and how it

fits with natural processes, which makes it possible to reasonably discuss the meaning of ribbed bedforms in glacial landsystem based on our experimental results (§5.3.).

4. “The natural sites appear to have been based on a ‘search and find features’ strategy. I understand the rationale of doing this, but it introduces possible bias that may have an impact on the analysis and conclusion. This limitation should be acknowledged and discussed. It would be useful to identify some strategies to further assess the validity of the comparison exercise.”

We agree that the mapping of ribbed bedforms along ice stream margins has been based on a ‘search and find features’ and that the small sample questions on the statistical representativeness of our observations. In this study, the aim is to demonstrate that ribbed bedforms form with characteristic shapes below lateral shear margins and frontal lobes of ice streams, as the experiments suggest it. We illustrate this suggestion through a selection of four sections of palaeo-ice stream beds, even other natural examples of oblique ribbed bedforms bordering lateral ice stream margins occur in the south of Wollaston Peninsula (69°12’N; 111°55’W), in the northeast of Ireland (54°1’N; 7°28’W) and in several sectors of the Scandinavian Ice Sheet (Szuman et al., 2021) for examples. Despite those observations, we agree that the kind of ribbed bedforms we present in this study were probably not systematically formed or preserved below lateral shear margins and frontal lobes of palaeo-ice streams, what must be highlighted in the discussion (see modifications in §5.1.). Consequently, several future investigations have to be realized in order to test the hypothesis that ribbed bedforms could be a morphological criterion to identify large-scale lateral or longitudinal velocity gradients (e.g., lateral shear margins and frontal lobes of ice streams). We suggest to (i) investigate a larger sample of palaeo-ice stream beds in order to explore the conditions of preservation and formation of these characteristic ribbed bedforms along their margins (see §5.1.) and (ii) prospect large-scale corridors and belts of ribbed bedforms in order to search if they could fit with hitherto non-recognized palaeo-ice streams (see §5.3.1.).

5. “In the analogue model, ribbed bedforms developed obliquely to the flow direction

near the lateral margins. Similar oblique features are also described such as near the lateral margin of the Amundsen Gulf ice stream. [. . .] Considering the results of their analogue modelling experiments, the authors propose a new interpretation [. . .], which is that these oblique lineations formed under the same ice stream configuration than for the younger glacial lineations that crosscut them. The crosscutting relationship between these features clearly indicate the oblique ribbed bedforms must have formed at an early stage. Furthermore, this two-stage process also brings the question of preservation. Are they observed near lateral margins because that is where they formed as oblique ribbed bedforms, or because older drumlins were better preserved there (i.e., only partially overprinted) due to lower flow velocities and patchy overprinting? It is an interesting idea to suggest they may have formed during a single phase (it would require at least a two-stage process) without any change in the configuration of the ice stream, but it remains to be tested. [. . .] In summary, if the oblique bedforms formed in an earlier phase and were overprinted and drumlinized later by the streaming bed, their spatial distribution could reflect more the area of better preservation potential (erased more in the middle of the trunk than on the lateral edges). Are they ribbed bedforms from a single phase or palimpsest/overprinted drumlins turned into ribbed bedforms following a shift in ice stream configuration? I think the question remains open in my opinion."

The bed of the Amundsen Gulf Ice Stream (AGIS) display a complex assemblage of two symmetric fields of oblique and elongated bedforms along both lateral margins of a trunk, characterized by a swarm of streamlined bedforms parallel to the trunk axis. The internal part (i.e., close to the trunk axis) of oblique bedform fields is partially overprinted by lineations with an orientation identical to the streamlined bedforms observable along the trunk. Those morphological observations fed two hypotheses in the glacial literature. Winsborrow et al. (2004) and Stokes et al. (2006), interpreted those oblique and crosscutting bedforms as three swarms of streamlined bedforms – preserved, partially overprinted or fully eroded – associated to different flowsets. Greenwood and Kleman (2010) think the same way, except that they interpret the

oblique and elongated bedforms occurring along the margins and partially overprinted by lineations as mega-ribs rather than streamlined bedforms. Based on experimental data, we suggest that oblique ribbed bedforms can form below lateral shear margins of ice streams, areas experiencing large-scale lateral velocity gradients, and develop peripheral to swarms of streamlined bedforms. We therefore propose that oblique and elongated bedforms described in the AGIS resemble in shape and pattern to experimental oblique ribbed bedforms and are potentially the same, with the difference that ribbed bedforms beneath the AGIS are apparently overprinted by lineations. This kind of oblique ribbed bedforms overprinted by streamlined features resembles (i) ribbed moraines with superimposed drumlins, both illustrating a single flowset (Greenwood and Clark, 2008), (ii) transverse asymmetrical drumlins (Shaw, 1983) and (iii) drumlins with an "en Echelon" arrangement (Clark, 2018). In parallel, the idea of a continuum in subglacial bedforms (ribbed bedforms, drumlins and MSGLs) emerged in recent modelling (Fowler and Chapwanya et al., 2014; Barchyn et al., 2016; Fannon et al., 2017) and palaeo-glaciological works (Stokes et al., 2013; Ely et al., 2016). Given that, it seems reasonable to propose a third hypothesis considering that drumlinized and oblique ribbed bedforms are an intermediate bedform between ribbed bedforms and drumlins. In this way, streamlined bedforms, and, oblique and overprinted ribbed bedforms can co-exist and form beneath a single ice stream undergoing spatial and temporal variations in flow velocity. Currently we cannot demonstrate this hypothesis but it needs to be considered. We clarify this discussion regarding the bedforms observable along the bed of the Amundsen Gulf Ice Stream and clearly enounce that the significance of oblique and drumlinized ribbed bedforms remains an open question with distinct hypotheses (see modifications in §5.1.).

6. "Based on my above comments, I think it is premature to conclude that we now have new criteria for palaeo-glaciological reconstructions."

We agree that our suggestion to interpret specific kind of ribbed bedforms as an additional morphological criteria to identify palaeo-ice stream margins is based on a reduced natural sample (Major comment 4.) and in certain cases on a new interpretation of bedforms (Major comment 5.). Even if a future overview of palaeo-ice stream margins will be necessary in order to validate this hypothesis, with regards to experimental and natural results presented in this study, we believe that it is justified to propose that the ribbed bedforms can constitute a new and supplementary criteria for palaeoglaciological reconstructions, especially in identifying ice stream margins In the revised version of the manuscript, we keep and discuss this hypothesis (see modifications in §5.3.1.).

7. "The authors do recognize that ribbed bedforms and abrupt lateral and down-ice transitions with glacial lineations have been documented and interpreted to record large velocity gradients across the bed (near line 640). However, they say that these previous interpretations were only for very local sticky spots, which seems to suggest that they are of limited significance or that they could not apply to their case. I think that the ideas presented in this study are in many ways quite close to what was presented in these earlier publications. For me, this new study is interesting because it may provide a new way of testing these ideas. [. . .] There has been an emphasis on mapping and using flowsets in palaeo-ice stream studies, but ribbed bed forms also provide key insights and thus deserve more attention because they can help understand the spatial patterns of sticky versus slippery portions of the bed, which is critical to understand ice stream dynamics and evolution."

It is now a widespread idea that ribbed bedforms form were ice slows down either at short (i.e., sticky spots; Stokes et al., 2007, 2016) or large scale (i.e., onset area of ice stream and ice dome; Aylsworth and Shilts, 1989; Dyke et al., 1992; Hättestrand and Kleman, 1999; Greenwood and Kleman, 2010; Stokes, 2018). Consequently, the formation of ribbed bedforms thus provide some key information regarding the ice velocity pattern and the spatial variations of sticky and slippery portions of bed, controlled by basal thermal regime, bed rheology and hydrological conditions. Experimental results confirm this idea and demonstrate that ribbed bedforms with specific shapes and ori-

entations develop below lateral shear margins and frontal lobes of ice streams, where lateral and longitudinal velocity gradients occur in response to variable hydrological conditions along the basal interface. We agree that the conditions responsible for the formation of ribbed bedforms both in local sticky spots and along ice stream margins must not be opposed. Indeed those conditions confirm that the formation of ribbed bedforms is controlled by the spatial pattern of sticky versus slippery portions of the bed, whatever their scale. We rectify this point in the revised version of the manuscript (see §5.3.1.).

8. "I am wondering if the long section that reviews the palaeo-ice stream landsystem is necessary. The rest of the paper focuses more on ribbed bedforms. [. . .] The text of section 2 could be considerably reduced. I think it would be sufficient to just summarize the conceptual model in the paper with appropriate references and use that space to present and discuss the assumptions, advantages, and limitations of analogue modelling for glacial dynamics problems."

We agree that our review section of palaeo-ice stream landsystem is long compared with the main purpose of the paper, the ribbed bedforms. Consequently, we reduce the state-of-art section (§2.) and focus on the ribbed bedforms, their shape, their spatial distribution and their formation processes. We also add a new section discussing the advantages, the limitations and the physics of silicon-water-bed interactions in the experimental model (§3.1.3.).

Minor comments

Line 34: Literature from the last 20 years is missing here. References "Kyrke-Smith et al., 2014" and "Minchew & Joughin, 2020" are added in the revised version of the manuscript (see §1.)

Line 184: I agree with this. In most places I am familiar with, ribbed moraines tend to be variably overprinted/reworked, mostly by drumlins that have formed at a later stage (most cases). "Moreover, ribbed bedforms are frequently overprinted by drumlins and embedded within polygenetic landsystems, corresponding to multiphase stories, which complicates their interpretation" (see §2.3.)

Line 203: So, it is four processes; not three as listed above. We corrected this error (see §2.3.)

Line 214: I note this is the density of water at 20deg. C. Any implications for modelling ice-bed interface near the pressure-melting point? Modelling experiments are realized in a laboratory with constant temperatures lying in between 15 and 20°C. We consequently do not reproduce the effects of temperature dependence on the silicon-water-bed system, as frozen basal conditions and melting processes. It constitutes a limitation of our experimental model, now mentioned in the dedicated §3.1.3. section of the revised manuscript.

Line 218: ". . . within the bed and along the silicon-bed interface"; in all directions or along one particular direction? Same question also for line 278. . . A fraction of the injected water (75%, see Lelandais et al., 2018 – Section 2.1) flows within the permeable bed in all directions from the water injector. The discharge of injected water is calculated beforehand so that water pressure exceeds the combined weight of the sand and silicon layers, and to allow the flow of water at the silicon–substratum interface. Water at the silicon-bed interface first accumulates above the water injector and forms the water pocket. Once a preferential direction for water routing is established during the water pocket migration (see Major comment 2.), the water flows in the same specific direction during the rest of experiment.

Line 289: The feature is referred to as a 'delta' here, but it is not controlled by water level in a frontal water body. It would be more accurate I think to refer to it as a 'splay' or a fan. First, all sediments deposited at the exit of sub-silicon conduits are deposited beneath water, indeed water accumulates around the silicon cap through the experiments as we keep injecting water. We partly agree with your comment above. In the very first stage of channelization and tunnel valleys development in the experiments, subaqueous fan

in contact with the silicon forms, at this time sediment deposition is not controlled by water level and no stream-deposited topset is observed (see ice-contact fan definition by Lønne, 1995). However the fan builds up quickly to the water-level and evolve into an ice-contact delta where channelized stream deposits form topsets at the top of the delta in its proximal area (see ice-contact delta definition by Lønne, 1995). We made sure that this distinction is clearly written in the revised version of the manuscript.

Line 326: "similar" . . . Data would be useful here rather than having to rely only on visualization and terms like "similar". The similarity between experimental and natural ribbed bedforms is based on qualitative data (bedforms with an undulating crest that form transverse to oblique to the flow direction) and quantitative data (elongation ratio, l/w = 3-4, and periodicity, with a wavelength slightly higher than their width). Even those data are already described both in sections §2.1. and §4.1.1. for natural and experimental ribbed bedforms respectively, we clearly write those data in order to argument this comparison in the revised version of the manuscript.

Lines 515/16: That is excluding the possibility that on the lateral edges there could have been drumlins instead of MSGLs. I think without local information about ice flow phases (e.g. from striation data) the previous interpretation of palimpsest landscape cannot be eliminated. See the response to Major comment 5. for more details.

Line 570: This is interesting. It would be important to link to the real case examples to support that statement. The ribbed bedforms mapped in this study along the lateral shear margins of the Amundsen Gulf Ice Stream, the Hay River Ice Stream and the Central Alberta Ice Stream display elongation ratio of 4.2, 2.9 and 3.8 respectively. The comparison classic ribbed/Rogen moraines (elongation ratio = 2.5; Dunlop and Clark, 2006) confirm our suggestion that real cases examples of ribbed bedforms observed below lateral shear margins present high elongation ratio because of the specific stress condition under which they form.

Line 657: I would like to point out that long corridors or tracks of ribbed bedforms alternating with narrow corridors of drumlins occur in places like northern Manitoba and in mainland Nunavut. They form some kind of 'bar code' landscape (see Fig.1 and Fig.3 in Trommelen et al. 2014). The banding is probably too narrow and laterally repetitive to represent separate ice streams and ice stream margins, but it does suggest lateral and regular variation in basal stick-slip conditions. We agree that the observation of ribbed bedforms clustered into corridors and belts, similar to belts reproduced it in the analog model, should not be interpreted restrictively as potential margins of palaeo-ice stream. As mentioned in our response to the Major comment 7., the formation of ribbed bedforms is controlled by the spatial distribution of sticky and slippery bed. Consequently, a future detailed mapping of long parallel corridors alternating with ribbed bedforms and lineations, as it is observed in northern Manitoba and near the Lake Naococane for examples, could provide information regarding the lateral and regular variations in basal stick-slip conditions. Based on our experimental results, corridors of oblique ribbed bedforms could potentially illustrate bands with shear deformation resulting from lateral velocity gradient. This point is now clearly nuanced in the section §5.3.1. of the revised manuscript. We are also more exhaustive regarding the ice dynamics and basal condition information that long corridors of oblique ribbed bedforms could provide.

Line 708: “development”. Development or preservation? In real cases, they could be distributed like that because they were crosscut by channels. In other words, perhaps they were more widespread and laterally continuous in an early phase and then later crosscut/eroded by meltwater channels. We agree that some ribbed bedforms are crosscut by channels and were more widespread and continuous before this crosscutting/erosion phase. However, one interpretation made in this study – based on experimental and natural observations – is that formation of channelized features below a frontal lobe generates longitudinal shortening stress along the coupled basal interface in between channels and triggers the development of submarginal ribbed bedforms, resulting from compressive bed deformation. Even if the channelization of water below lobes erodes submarginal ribbed bedforms and preserves them in between the asso-

ciated channels, it firstly allow the formation of ribbed bedforms. That’s why we keep the term “development” in the revised version of the manuscript.

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