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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: Richard Hindmarsh

We thank Richard Hindmarsh for its very useful comments which have helped us to improve the quality and the precision of the manuscript. The major points raised by Richard Hindmarsh were regarding the discussion of processes occurring in the experimental model, with a focus on the physics involved in the formation of experimental bedforms compared to those of their natural counterparts. In section §2., the overview

of glacial landforms was reduced and refocus on ribbed bedforms descriptions and formations only. We would like to recall in this regard that the label "ribbed bedforms" used throughout the manuscript is purely descriptive and does not possess any implications in terms of formation processes. We did this to deliberately set a distance between the novel experimental observations we report and those in nature because uncertainty remains as to how closely connected they are. We suggest that some of the review comments have perhaps mistaken us to be saying that our experimental ribbed bedforms are ribbed moraines. In order to compare natural and experimental features, 'ribbed bedforms' gathers in a single label all the subglacial periodic ridges that are formed transverse or oblique to the ice flow direction with a ribbed appearance (excluding crevasse squeezed- ridges). Replies to referee's comments are addressed below in red. Annotations (1.) refer to paragraphs of review responses while annotations (§1.) refer to manuscript paragraphs.

Kind regards, Jean Vérité (on behalf of all co-authors)

1. "V++ rather steer clear of the viscous/plastic debate; they cite the ur-viscous paper (Boulton and Hindmarsh, 1987) but cite nothing by Terzaghi nor by Kamb." References regarding works of Terzaghi (1931), Kamb (1991) and Tulaczyk et al. (2000) on the plastic rheology of sub-glacial till were added in §2.3., which present the distinct formation processes, according to till rheologies, of ribbed bedforms.

2. a) "Their work does produce flow-transverse ribs, but does not produce features aligned with flow that resemble either drumlins or mega-scale glacial lineations. This raises the question of why do their experiments not produce the whole gamut of glacial geomorphology?" Except the hypothesis of "large-scale subglacial meltwater flood events" evoked by Shaw (2002), all the hypothesis regarding the formation of subglacial bedforms are associated to a till or a sedimentary substratum being coupled to an overlying ice sheet that flows and either deform and remould its bed. Streamlined bedforms (e.g. drumlins and MSGL), as opposed to transverse bedforms (e.g. ribbed bedforms), are mostly explained as formed beneath corridors of high ice flow velocity

(Clark, 1993; Stokes and Clark, 1999; Stokes et al., 2013). In our experiments, we inferred that ribbed bedforms are formed where the silicon cap and the bed are coupled (i.e. unlubricated interface) and where silicon flows 10ˆ1 times faster than the surrounding silicon cap. By comparison, silicon stream trunks – where ribbed bedforms do not form – exhibit velocities up to 3.10ˆ1 times faster than the surrounding silicon cap. The only way to trigger a fast-flowing corridor in the silicon model is to initiate decoupling above a pressurized water film. Where silicon flows the fastest (within the silicon stream trunk) the silicon-bed interface is thus entirely decoupled, therefore explaining the lack of drumlins and MSGL in our experiments. The maximum silicon flow velocity we experimentally reproduced in the silicon-bed coupling zones where ribbed bedforms develop is probably insufficient to initiate streamlined bedforms (see modifications in §5.2.2.). Indeed, the presumed velocities that enable drumlins and MSGLs formation are 10ˆ1 or 10ˆ2 times faster than where ribbed bedforms form, respectively (Stokes et al., 2013 - Fig.17).

b) “and brings us back to the question above about the physical realism of their simulations: are their laboratory ribs formed by the same set of processes that form subglacial ribs?” We agree that it is major point of the review to deepen the understanding of the formation process of experimental ribs and to determine if this process is compatible with those described in the literature. We now demonstrate that experimental ribbed bedforms are produced where the silicon cap is coupled to its underlying bed and the silicon undergone lateral or longitudinal velocity gradient because of heterogeneities in basal water drainage. The high basal shear stress generated by the coupled flow of silicon over the bed is responsible for bed deformation, characterized by the rotation and the boundary sliding of grain along intergranular shear planes (see the new Fig. 15 and modifications in §5.2.1.). The deformation of the bed initiates the formation of experimental ribbed bedforms and allows their growth. Experimental ribs thus form and elongate perpendicular to the shortening axes and parallel to stretching axes of silicon strain ellipses, and are consequently seen as controlled by silicon deformation. In this reviewed version, we decide to overfocus on the comparison of

shape and elongation of experimental ribs with superficial strain axes rather than flow directions (see modification of Figs. 7, 9, 14 and S2 and modifications throughout §4.). In the glacial literature four classes of formation processes are invoked to explain subglacial ribs (see §2.3.), and one is compatible with the process invoked to explain the formation of experimental ribs (see §5.2.2.). They consider (i) a deformable till layer – either with a plastic (Shaw, 1979; Bouchard, 1989; Lindén et al., 2008; Stokes et al., 2008) or a visco-plastic rheology (Hindmarsh, 1998a,b; Fowler, 2000; Schoof, 2007; Dunlop et al., 2008; Chapwanya et al., 2011; Fowler and Chapwanya, 2014; Fannon et al., 2017) –, flat and temperate, whose (ii) deformation results from the shear stress induced by the coupled flow of ice over an active till layer. The deformation of active till layers, in both rheological configurations, enables the formation of periodic subglacial ridges transverse and oblique to ice flow direction. As our experimental model has the same pre-requisite conditions (i and ii) and reproduces periodic ribbed bedforms, we consider that laboratory ribs can form by processes compatible with some existing theories of ribbed bedforms formation.

3. “The glacial geomorphology descriptions should be reduced substantially; I don’t believe that, compared with their length, they contribute anything amazingly new. Rather, V++ should make the points that ribs, drumlins and MSGL exist, and V++ can simulate rib-formation.” We agree that our inventory of glacial geomorphological was too exhaustive and too long regarding the main purpose of the paper: ribbed bedforms. Consequently, as a preamble of §2. we briefly introduce the different subglacial bedforms (ribs, drumlins, MSGL and hummocks) without detailed description, we deleted the sections dedicated to (i) streamlined bedforms, (ii) marginal and submarginal landforms and (iii) shear moraines. We focus §2. on ribbed bedforms and their morphological characteristics (§2.1.), their spatial distribution in glacial and ice stream landsystems (§2.2.) and their theories of formation (§2.3.).

4. “More attention to the basic physics is required; how did V++ estimate ice pressure, water pressure and effective pressure? From their plentiful quotations of theoretical

work by the viscous-till school it seems that they do not oppose this idea on fundamental grounds, so V++ should include more detailed analyses of how their observations of the component pressures relate to HFS." As mentioned in 2.b, the pre-requisite basal conditions ("(i) a deformable till layer, flat and temperate, whose (ii) deformation results from the shear stress induced by the overlying ice") and the bedforms reproduced in the laboratory support the viscoplastic-till theory, which consequently has to be physically tested. We totally agree that the distribution of effective pressure – potentially responsible for sediment flow and rib initiation – should be measured and monitored in order to better constrain the formation processes of experimental ribs. However, the technical limits of the experimental device do not allow to estimate the water and effective pressure at the scale of a single ribbed bedform. Twelve sensors measure the pore water pressure below the circular silicon cap, meaning we have two or three sensors below the silicon stream at most (see Fig. S3). Therefore, interpolating pressure maps at the stream scale would already be presumptuous and would not provide representative data at the bedform scale.

5. "My ideal paper form is [. . .] §2. - review of glacial geomorphological features produced under the ice, with an emphasis on rib descriptions (perhaps contrasting Rogen moraine and traction ribs) and on the viscous (and other) theories of rib formation; [. . .] ; §4. - a discussion of how the experimental set-up permits and/or disallows experimental observations that confirm existent theories." We thank the reviewer for this proposition and we agree with it. §2.: We agree with the remoulding of §2., with a more detailed and precise description of the distinct type of ribbed bedforms (a purely descriptive term gathering Rogen and ribbed moraines, traction ribs, mega-ribs and possibly other rib types yet to be described), notably regarding their wavelength and dimension compared with ice thickness. The different theories of ribbed bedform formation, their associated physics and the till rheology are now explicitly described. §4: As suggested by the reviewer, we added in the revised version of the manuscript new sections discussing the model and the experimental bedform formation. We discuss in this new section (§3.1.3.) the pros and cons of the experimental set-up in reproducing the subglacial environment processes, the subsilicon physical conditions and the silicon-water-bed interactions, notably regarding the subglacial processes we are able to reproduce or not. In §5.2.2., based on experimental results, we now discuss the compatibility of experimental ribbed bedforms with existent theories and lack of streamlined bedforms in our experimental landsystem.

6. "A newish feature of the analysis in V++ is the association of rib-field locations with particular locations in ice streams and ice sheets. This possibly leads V++ to overfocus on these - for example rib co-location with stream lateral margins and downstream ends of surge lobes - and ignore the widely agreed observation that rib fields are found upstream of drumlin fields, under slower-flowing portions of the ice sheet. Do V++'s results explain these?" Our experiments only produced ribbed bedforms in the locations we show and this is why we focus on these. Because the experiments did not produce drumlins or MSGLs, we cannot explain the ribbed moraine to drumlin transition. Also, we don't yet know whether the ribbed bedforms we describe in places across sharp velocity gradients (fast to slow) also occur across slow-to-fast gradients, and indeed whether they are even the same 'type of ribs' with the same process, or perhaps different things. Consequently, we agree that §2. had to be reshaped in order to overfocus on (i) the processes of ribbed bedforms formation, and on (ii) their spatial distribution, notably regarding their observed relationship with ice stream margins and velocity gradients. Although ribbed bedforms are more frequent below slow-mowing part of ice sheets, they have also been observed along palaeo-ice stream beds (e.g. Stokes et al., 2008, 2016; Moller, 2006, 2010; Stokes et al., 2016) and associated with regions of high velocity gradients between rather stagnant ice-sheet and fast-flowing ice (along borders of ice stream trunks or around subglacial sticky spots).

7. "The dependence of deformation rate on effective pressure (difference between the load exerted by ice and water pressure) was central to understanding how the instability arose; a particular point is that the dependence of flux on effective pressure affects the distribution of negative flux gradients (where the till is thickening). I would

like to see more consideration of how V++'s mechanisms of rib formation might be explained in terms of the Fowler-Schoof conditions." Comparing maps of silicon deformation rate and effective pressure, with maps of analog subglacial features would be fascinating and could potentially reconcile communities of palaeoglaciologists and glacio-physicians. However the current experimental device does not allow to produce high-resolution effective pressure maps (see 4. for more details).

8. "There is considerable focus in recent literature on the horizontal dimensions of the landforms compared with the thickness of the ice. [. . .] I recognise that in the past decade two 'species' of ribs have come to be recognised, the long-established ribbed/Rogen moraines with spacings of 300 - 1000 m ($\leq$ ice thickness), and the newer larger 'traction ribs' (Sergienko and Hindmarsh, 2013; Stokes et al., 2016) with spacings of a few kilometres ($\geq$ ice thickness); these traction ribs can be found underneath ice streams in non-traditional rib locations. [. . .] I encourage V++ in their resubmission to provide data on the rib spacings and how this compares with the silica gel thickness at time of rib formation" The wavelength of experimental lateral and submarginal ribbed bedforms lies in between 7 and 19 mm, and, 10 and 15 mm respectively. The rib wavelength tends to remain constant once lobe stabilizes and thinning rates of the silicon layer reduces (i.e. as the lobe advances, by conservation of mass, the stream becomes thinner). For a stabilized lobe, the profile of silicon thickness slowly decreases up to the margin and the column of silicon is closed to 20 mm above the lateral ribs (i.e. formed below shear margins) and between 5 and 15 mm above the submarginal ribs (i.e. formed below lobes). The experimental rib wavelength lies in between 0.4 and 1.5 silicon thickness, and thus tends to form with a spacing slightly lower than or equal to the cap thickness. Experimental rib characteristics compare quite well with traction ribs whose spacing is equal to or greater than ice thickness (Sergienko and Hindmarsh, 2013; Stokes et al., 2016), while ribbed and Rogen moraines exhibit a spacing (Dunlop and Clark, 2006) almost an order of magnitude less compared with ice thickness (Paterson, 1972). This new morphometric argument in favour of experimental ribs similar to traction ribs is now added in §5.1. However, to establish a semi-quantitative law

comparing the evolutions of bedform wavelength and cap thickness from experiment model would not be suitable since the silicon-bed system is physically different from the ice-till system.

9. "If the horizontal dimension is less than or comparable with the ice thickness, the full Stokes equations need to be solved in order to calculate the normal stress exerted by the ice on the sediment accurately; this is needed to calculate the effective pressure. [. . .] They could also comment on how their observations coordinate with the Fowler-Schoof conditions for geomorphological instabilities to exist. [. . .] It is almost certain that modelling traction ribs requires solution of the Stokes equations, despite their large horizontal dimensions, owing to the slippery beds (low 'traction number') beneath streams (Hindmarsh, 2004; Schoof and Hindmarsh, 2010)." Although experimental ribs display horizontal dimensions similar to traction ribs, technical limitations of the experimental device do not allow to solve Stokes equations and to test Fowler-Schoof conditions. With the resolution of current pressure measurement, we are not able to calculate effective pressure at the scale of ribbed bedforms. Despite this technical inability to quantitatively/physically test theories of rib formation, our experimental model enables us to discuss the distribution, the orientation and the formation timing of ribs compared to ice and meltwater flows; and thus to discuss similarities between our experimental model and existing theories.

10. "A substantial proportion of theories of rib-formation (e.g. Hättestrand and Kleman, 1999) focus on the freezing-melting boundary map-location as a control on rib formation. V++'s experimental set-up does not permit investigation of this aspect, but this matter does require some comment, in particular on the issue of whether, subglacially, there is one and only one means of forming ribs." Experiments are realized in a laboratory whose temperature lies in between 15 and 20°C that consequently do not reproduce frozen basal conditions. An experimental frozen-bed will also limit the formation of bedforms by increasing bed stiffness and cohesion, and reducing the bed deformability and erodibility. One theory of rib formation, established by Hättestrand

and Kleman (1999), suggests that transition in the basal thermal regime could induce frozen bed fracturing and cause the formation of ribbed bedforms. As mentioned in 2.b, this theory is not testable with our experimental device since the bed is temperate. Others theories however exist and ribbed bedforms might be formed through several means (§2.3.), one of which invoked bed deformation in response to the coupled flow of ice, water over a deformable till layer and is compatible with our model (§5.2.2.).

11. “Were ‘faults’ observed, and what does this tell us about the styles of deformation?” No faults are observed within the sedimentary bed at the scale of experimental bedforms. The mean height (hmean) of analog ribbed bedforms is equal to more or less 1mm while the median grain size of the bed is dmed = 100μm (i.e. a rib is composed of up to 10 sand grains). Although it might be very hard to distinguish any structures in homogeneous sand bed considering the size of the ribbed bedforms, cross-section making are very difficult to make because they tend to destroy the structures due to pressure exerted on the water-saturated bed and the silicon during the realisation of slices through the model. Given the bed is constituted of unconsolidated and water-saturated sand with very low cohesion, and almost equant grains lack a clear lattice-preferred orientation, we assume that the bed undergoes ductile deformation through transfers of sediments at grain-scale through grain boundary sliding, translation and rotation possibly along intergranular shear planes in the upper active bed (Hamilton et al., 1968; Oda and Konishi, 1974; Owen, 1987; Bestmann and Prior, 2003). Considering the size of our experimental ribbed bedforms, these intergranular shear planes might correspond to “faults” in nature (see modifications in §5.2.1. and the new Figure 14).

12. “Some thought needs to be put into explaining why the experiments do not produce flowaligned features (drumlins/MSGL) in the context of work by the Fowler-school modelling of drumlin formation. I appreciate that a definitive answer may not be available yet, but this would be of considerable benefit to those wishing to extend and elaborate the work of V++.” Whatever the till rheology, viscoplastic (Hindmarsh, 1998a,b; Fowler,

2000; Schoof, 2007) or plastic (Terzaghi, 1931; Kamb, 1991; Tulaczyk et al., 2000), the ice flow transmits a shear stress to an active till layer when the ice is coupled to its bed, thus triggering bed deformation and bedform initiation (ribs, drumlins and MSGLs). The only difference being that numerical models considering a viscoplastic till rheology are able to quantitatively predict bedform spacing and produce timedependent bedform evolution (Fannon et al., 2017). Regardless of the till behaviour, it is assumed that mega-scale glacial lineations are thought to be formed under high flow velocity or longer duration than drumlins, and even higher than ribs. Some studies suggest that ice velocity is a key parameter considering the modelled basal velocities and the improbability of constant and straight ice flow for hundreds of years during deglaciation periods (Clark, 1993; Stokes et al., 2013). Based on these arguments and on those enounced in 2.a about the experimental stream velocity, it is probable that silicon velocities are insufficient to initiate streamlined bedforms or to generate ribbed bedforms evolving into drumlins, while the fundamental basal processes are met (see modifications in §5.2.2.).

13. “Since glacier linked-cavities rely on cavity formation and hydraulic links between the cavities, V++’s association of laboratory-observed networks with ‘linked cavities’ is quite reasonable, but R-channel theory relies heavily on the heat production by flowing water melting the tunnel that is being closed by the weight of the ice; thermal effects are not included in V++’s experiments. A related point is that R-channel theory and linked-cavity theory have opposite relations between the system transmissibility (product of permeability and vertical area) and effective pressure; Rchannels have transmissibility increasing with effective pressure, while linked cavities have it decreasing. It is not clear whether the dynamics of the sub-silica drainage system are the same as the sub-glacial; for example, might not the lab drainage system development be due to a Hele-Shaw instability? It might be that V++ wish to point out the similarities between the mechanisms of their lab-formed streams and streams in the field, but the real question is whether sufficient observations have been made in either case; I’m pretty sure that not enough is known about stream-formation in nature.” Sub-silicon drainage sys-

tem is composed of three type of drainage features: (i) water film corresponding to the distributed and widespread flow of water below the experimental ice stream (Breemer et al., 2002; Le Brocq et al., 2009); (ii) linked cavities corresponding to interconnected water spots in between ribbed bedforms (Fowler, 1987); and (iii) N-channels (rather than R-channel) corresponding to meltwater channels and tunnel valleys carved in the sedimentary bed (Madsen, 1921; Nye, 1973). As the silicon putty cannot reproduce the ice–water phase transition and the temperature does not affect silicon putty properties, sub-silicon water flow cannot generate Rchannels. Hele-Shaw instabilities can occur at the interface of two fluids (of distinct viscosities as water and silicon putty) flowing at different velocities, and generate periodic wave-like features transverse to the interface. It is therefore unlikely that this instability is responsible for the formation of the drainage system. In our experiment, N-channels develop in response to the erosive flow of pressurized water that carves channelized features into the bed (Lelandais et al., 2016). They form in order to improve the effectiveness of the water drainage system, draining water from the highpressure water film to the low-pressure marginal area. Those mechanisms are similar to processes responsible for meltwater channelization in subglacial environments (Fountain and Walder, 1998; Kehew et al., 2012; Lelandais et al., 2016; 2018). Experimental linked-cavities develop when the bed surface becomes no longer flat and bedforms grow. Water from the water film spreads in between those topographic obstacles, notably in the lee-side of ribbed bedforms. As experimental ribs are organised into fields, cavities are interconnected and constitute a water drainage system at the silicon stream margin similar to subglacial linked-cavities (Fowler, 1987; Hooke, 1989).

14. “V++ do not include thermally-based mechanisms in their experiments, which leads naturally to wondering about their lab-produced ribs adjacent to stream boundaries is this saying (as they seem to be suggesting) that one condition for rib formation is a large lateral velocity gradient - a glaciological insight of potentially great importance - or are there some special thermal characteristics near ice-stream margins at the bed that are the primary cause of rib-formation?” A consequence of thermal mechanisms along

the basal interface of glaciers is the subglacial production of meltwater able to initiate, in certain cases, decoupling between the ice and its bed. In areas where the bed is permeable or where meltwater production is absent, ice-bed coupling predominantly occurs. In the experiments, the spatial transition in meltwater availability and drainage types between mostly coupled areas (e.g. lateral shear margins and lobe margins) and decoupled areas (e.g. silicon stream) induce flow velocity gradients. Beneath the silicon shear margins, lateral velocity gradients between the silicon stream and the stagnant surrounding cap generate high basal shear stress being accommodated through bed deformation and ribbed bedforms formation. Ribbed bedforms formation in our experiments is thus primary conditioned by the transition of the basal meltwater drainage (not reproduced by thermal variations in the model but by injection of water beneath the silicon; see §3.1.3.), which induce velocity gradients delineating the ice stream margin.

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