Review of "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 and ten others for *The Cryosphere*

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1 Overview

This paper by Jean Vérité and colleagues (V++) from *Le Mans Université*, *Université de Nantes*, University of Sheffield and Alberta Geological Survey addresses a centuries-old topic in glacial geomorphology, namely the mechanisms operating and conditions needed to produce certain glacial geomorphological landforms (ribs and drumlins); they focus on ribs transverse to the ice flow direction. V++ adopt an approach of performing laboratory experiments; the authors give the impression of being good and experienced at these and are also very enthusiastic. They use an integrated approach, simulating the ice sheet with a pancake of flowing silica gel, which overlies sand, and pump water in underneath in order to lubricate the base. The tray on which they do this is $2\text{m}\times2\text{m}$, and the ice sheet, at least at the start of the experiment, has a roughly circular profile. They report on fifteen of these experiments, with conditions varied. Presumably for practical purposes, they do not include thermal effects in the experiment, in particular lab representations of the transition between ice and water.

During the experiments, water is pumped in underneath the silica gel, at a central location: the higher water pressure causes the silica and sand to disassociate, and for silica streams to form, which V++ compare with ice streams. V++ are aware of the two styles of sub-glacial drainage that have received greatest attention, 'R-channels' (Röthlisberger, 1972) and 'linked cavity systems' (Kamb et al., 1985) and identify both as forming in distinct experiments. R-channels form dendritic systems, while 'linked cavities' are networks.

The title of the paper "...reveal shear margin positions, lobe shutdown and the interaction of meltwater drainage and ice velocity patterns" indicates that they wish to focus on some previously underconsidered aspects of geomorphology. The reasons for these choices become clearer as one reads the paper; the lab experiments produce rib forms in what glacial geomorphologists might regard as unusual locations, and V++ wish to emphasise the spatial realism of their results. This of course a very reasonable approach, but the cautious reader might well start to wonder whether the processes involved in the creation of structures in the lab are the same as those which produce structures in the field. V++ should pay rather more attention to this, considering the detailed physics of both situations.

Glacial geomorphology has undergone quite a substantial change in the past quarter-century; previously it was carried out by geologists and geographers, who did not consider in detail the physics and mathematics of the processes. In the late 1990s theoretical work was done on the coupling between ice and deforming sediment beneath, which turned out to make quantitatively accurate predictions of rib-spacing (though successful models of drumlin formation had to wait a decade or more). This initial work was done primarily and independently by Hindmarsh (1998a,1998b), Fowler (2000) and Schoof (2007) (these papers abbreviated *HFS*), with substantial later contributions from the 'Fowler-school' - Chapwanya, Katz, Kyrke-Smith and Fannon.

Despite its successes, this work has not been widely accepted, owing to its use of a viscous rheology to describe the deformation of till; laboratory experiments carried out in the 1930s by Terzaghi and in the 1990s by Kamb indicated that reproducible results in the laboratory could only be obtained with a plastic rheology. However, the plastic rheology has yet to produce a theory that predicts landform formation such as ribs or drumlins. As Fowler (2010, p.970) puts it "*This suggests that the simplest conceptual model for till deformation is already much more complicated than either a viscous or perfectly plastic material, and that, where till is concerned, there is still a great deal of theoretical work to be done concerning the sliding law*". There is a debate in glaciology about whether till is plastic or viscous, and the answer seems to be that it is more complicated than this opposing pair approach admits.

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. They have plentiful descriptions of glacial geomorphological features (probably over-plenty); the point of this seems to be that their lab work produced various features, which resemble glacial geomorphological features, and they wish to bring this to the attention of the reader. Certainly, their work does produce flow-transverse ribs, but does not produce features aligned with flow that resemble either drumlins or mega-scale glacial lineations (MSGL, Clark 1993). This raises the question of why do their experiments not produce the whole gamut of glacial geomorphology? 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 sub-glacial ribs?

In V++'s favour is that in their experiments ribs are formed. However ribs are formed in nature by a vast variety of processes, for example sand ripples in streams and transverse cloud patterns; in both cases turbulence is involved, which is not held to be a major component in the formation of sub-glacial ribs. This widespread occurrence of ribbing leads the reader to wonder whether the ribs in V++ are produced by the same basic set of mechanisms as those operating beneath ice sheets and glaciers.

V++ presents novel exciting experimental work which will inspire a very large portion of the glaciological community, and should certainly be published, but I don't believe it to be publishable in its present form. 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; I emphasis 'simulate' because the authors do not make the case that their experimental formation processes represent precisely the same set of morphological processes as are operating beneath glaciers and ice streams. To this end, 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*.

My ideal paper form is §1: Introduction (much as it is now); §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; §3 - a description of the experimental set-up; §4 - a discussion of how the experimental set-up permits and/or disallows experimental observations that confirm existent theories; §5 - the results; §6 - a discussion of how rib-formation locations are related to ice-stream plan-geometry; §7 - Summary and conclusions. I have little doubt that the authors of V++ will disagree with some of these aspects, but they should recall that the main contribution of the paper is the experiments that they have carried out with panache, and emphasise that their results are largely *consistent* with (but not exactly identical to) nearly two centuries of geomorphological observations. Another way of putting this is that **none of their observations are never found in the field**, but that their silica-sand-water system might have different statistical characteristics from the ice-sediment-water system.

2 Major Points

The following points are thoughts that I had during the review; quite a few of them don't include specific suggestions to the authors. I think that all the sentences ending with a "?" need to be given consideration in the revision.

1. V++ §2 reads like a review paper on the glacial geomorphological features shaped by local glacial erosion and deposition (ribs, drumlins and MSGL). It is effectively a catalogue of such forms with little detectable relevance to the main purpose of the paper, which is to present the experimental results. Since the experiments did not produce features resembling drumlins or MSGL, the revised §2 should focus on ribs. 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?

2. Significant work on relating theory and observations of enormous sets of subglacial ribs was done by Dunlop and Clark (2006) and Dunlop at al. (2008) (in fact Chris Clark is one of authors of V++). One of the conclusions of Dunlop et al. (2008) was that their results, obtained from analysing 2×10^4 ribs, did not falsify the viscous theory of rib formation. Fowler (2000) and Schoof (2007) showed that 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.

3. There is considerable focus in recent literature on the horizontal dimensions of the landforms compared with the thickness of the ice. 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. 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. They could also comment on how their observations coordinate with the Fowler-Schoof conditions for (geo-)morphological instabilities to exist.

4. 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. 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).

5. 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, sub-glacially, there is one and only one means of forming ribs. My personal belief is that there may be several.

6. There doesn't seem to be a great emphasis on the fault and fold structure within and surrounding the ribs - a good deal of work on this matter (in glacial landforms) has been published e.g. *Hart et al.*, (1990, Figs. 3&4), *Eyles*, (1993, Figs 3.5&3.6). I appreciate that the sizes of the features will be rather different (V++ order millimetres, geologists order tens of centimetres) and that it is probably not possible to look at the lab-structures now, but some insight might have been gained during the experiments. Were 'faults' observed, and what does this tell us about the styles of deformation?

7. Some thought needs to be put into explaining why the experiments do not produce flow-aligned 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++.

8. 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; R-channels 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.

9. In particular, questions were raised in my mind about the mechanisms in the V++ experiments by which the streams were formed. Agreed that there are theories in

which streams are formed through the interaction of ice flow and water flow (via effective pressure) - Google on "Kyrke-Smith", "Katz" for a lead into this - but the first quantitatively-identified mechanisms were through thermo-viscous feedbacks (e.g. MacAyeal, Payne, Hindmarsh in the '90s). As mentioned above, 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?

3 Minor/Editorial Points

There are several of these but not enough to point out, given that a substantial revision will occur. The English is mostly excellent.

4 References

This is a list of all the papers I referred to in the review. Various works by the 'Fowler-school' (Chapwanya, Katz, Kyrke-Smith, Fannon) are cited in V++.

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