Answer to the referee's comments

We would like to thank Carrie Jennings and the anonymous reviewer for the careful reading of our manuscript and the helpful comments. Replies to referee's comments are addressed below (blue colored). Broadly speaking, both reviewer agree on the novelty of our experimental approach but ask for a more clarification on the limitations of the experiment.

Referee #1 : Carrie Jennings

General comments

"I appreciate this modeling attempt. I am not aware of any other work on modeling subglacial hydrology since G. Catania and C. Paola, 2001, Braiding under glass. Geology, 29(3), 259-262. I believe it is relevant and should be cited. Models inform our intuition. They cannot prove anything but they can lead us to a better understanding of physical processes if we understand the limitations of the model setup. I would like to see the model and its limitations more fully described. What about model is not like real world? What are the shortcomings? How could these shortcomings affect model results and deviate from real-world processes?"

The referee is right to point out that analog modelling provides intuitions and ideas on a specific process but does not constitute a proof. Experiments produce morphologies and dynamics that, although imperfect, compare well with natural systems despite differences of spatial scale, time scale, material properties, and number of active processes. Thanks to the numerous comments of the referee, we added (i) some restrictions on the interpretation of the experiments and (ii) the limitations of the model to reproduce its natural counterpart. An entire paragraph (section 2.3) is now entirely dedicated to the limitations of the model.

Specific comments – Abstract

L20 – 21. Do they ever evolve to be efficient drainage systems? Tunnels seem very short-lived and episodic to me and ice-streaming redevelops again and again. Your experiment represents a very coarse-textured bed when scaled up, so this may be an effect related to grain size.

In our experiments, tunnel valleys stay active during the whole experiment. Meltwater routing, dynamics of tunnel formation and evolution of ice stream dynamics are intricately connected during experiments. Figure 5 in the revised version shows that tunnel valleys, once reaching a certain overall volume, reduce the silicon flow velocity until the modelled ice stream switches off. This suggests that the tunnel valley system evolves in an efficient drainage system able to drain all the subglacial water, thus reducing water pressure and enhancing basal friction. Grain size has necessarily an effect on the drainage capacity of experimental tunnel valleys. The use of a substratum with different properties would probably change tunnel valleys amount and development rates.

Specific comments – Introduction

L32-33. drainage pathway for sediment...reword ?

We suggest to reword the sentence as:

"approximately 80% of the ice discharge is focused in a finite number of ice streams, which act as preferential drainage pathways for meltwater also (Bamber et al., 2000; Bennett, 2003)"

L34. Ancient ? Is palaeo a word by itself

We suggest to replace every use of palaeo by “ancient” or “former”.

L35. Is m. correct ?

We thank the reviewer for this comment. It is true that the classical way to write any ratio is to use a slash. We suggest modifying all the “m.s^{-1}” by “m/s”.

L37. How about the evolution ?

We suggest to modify the end of the sentence in: “and the controls on their dynamics evolution remain debated”.

L54. Reference for this? I think it relates to Ice Stream C and B in WAIS

We suggest to add Vaughan et al., (2008) and Carter et al., (2013) as references for the subglacial water piracy processes.

L68. ours are much shorter but formed in segments--or at least are interrupted by ice-marginal fans.

We modify the sentence to inform the range of tunnel valleys dimensions: “These valleys are elongated and over-deepened hollows, ranging from a few kilometres to hundreds of kilometres long, from hundreds metres to several kilometres wide and from meters to hundreds of meters deep.”

L72. not by all--this feels a bit like you are setting up a straw-man type argument.

We agree with the reviewer that this sentence was perhaps misleading. We suggest to rewrite as follows:

“Indeed, ice streams commonly operate because of high basal water pressure while the development of a tunnel valley system generally leads to enhances drainage efficiency and basal water pressure reduction (*Engelhardt et al., 1990; Kyrke-Smith et al., 2014; Marczinek and Piotrowski, 2006*).”.

L74-76. I would say that from the field evidence, there is a third process: 1) ice streaming; 2) drainage through tunnel valleys; 3) stagnation of the ice margin.

We suggest adding a sentence to explain that field studies have already suggested a link between outburst flood and a set of events involving ice streaming, tunnel valley formation and ice margin stagnation: “Several field studies have already suggested a connection between catastrophic glacial outburst floods at ice sheets margins and a suite of events involving ice streaming, tunnel valley development and stagnation of the ice margin. (*Bell et al., 2007; Hooke and Jennings, 2006; Jørgensen and Piotrowski, 2003; Alley et al., 2006*).”

L79. Bering glacier behavior during and after a surge comes close https://www.cambridge.org/core/services/aop-cambridge core/content/view/08A39D0DD9EBE9C32D232B7769B55728/S0022143000202311a.pdf/lacuna_band_surface_depressions_occurrence_and_conditions_of_formation_bering_glacier_alaska.pdf

This reference does not connect ice streaming with subglacial erosional processes so we choose to not add this reference because it is not appropriate with the meaning of our sentence.

L86. How would tunnel valleys influence the location of ice streaming if they only happen after streaming is already occurring? This may need to be more precisely worded.

We agree with the reviewer that this sentence requires clarifications. We suggest writing as follows:

“We propose that the location and initiation of ice streams might arise from subglacial meltwater pocket migration and drainage pathways and that the evolution of ice stream dynamics is latter controlled by subglacial drainage reorganization and tunnel valleys development.”

L86. This work ?

We suggest to writing as follows: “This study reconciles into a single story ….”

Specific comments – Experimental ice stream model

L94. partially overcome ?

We agree that this phrasing might not be the best one to explain that our model is useful to explore the connection between subglacial meltwater routing and ice dynamics without being a perfect representation of nature. We suggest to rewrite this section as follows:

“Considering all these processes and components simultaneously, together with processes of subglacial erosion, is thus a challenge for numerical computational modelling (*Fowler and Johnson, 1995; Marshall, 2005; Bingham et al., 2010*). Based on this statement, some attempts in analogue modelling have been made to improve our knowledge on subglacial erosional processes by meltwater (*Catania and Paola, 2001*) or gravity current instabilities produced by lubrication (*Kowal and Worster, 2015*). To combine ice flow dynamics and erosional aspects in a single model, we designed an alternative experimental approach that allows simultaneous modelling of ice flow, subglacial hydrology and sedimentary/geomorphic processes. With all the precautions of use inherent of analogue modelling, our experiments reproduce morphologies and dynamics that compare well with subglacial landforms and ice stream dynamics despite some differences of spatial and time scales and a number of active processes (e.g. *Paola et al., 2009*).”

L97. Paola et al., 2009--the way this is referenced now makes it seem like they simultaneously modeled these things.

We thank the reviewer for this clarification. See the modification made to answer the last comment.

L98. Use as an example? This is not the fundamental reference for the previous statement. Shreve, R.L. 1972. Movement of water in glaciers: Journal of Glaciology, 11(62), 205-214? or even earlier: Glen, J.W. 1952. The stability of ice-dammed lakes and other water-filled holes in glaciers. Journal of Glaciology, 2(15), 316-318.

We agree with the reviewer that it is not the fundamental reference and we added Shreve (1972) and Glen (1952) according to your proposition.

Line 99 : thus in part controlled by....This seems overly simplistic or at least backwards--active margins of ice sheets are an expression of mass balance, bed topography and ice surface slope

We agree with the reviewer that meltwater routing is function of many parameters. We suggest modifying this sentence so that we understand that ice slope is prevailing to control meltwater routing but that subglacial topography, and the mass balance also influence meltwater routes. We suggest to add a section dedicated to the limitations of the model (2.3 Scaling and limitations) and to rewrite this sentence as follows:

“Subglacial meltwater routing is indeed controlled by the ice surface, slope, the bed topography and the glacier mass balance (*Röthlisberger and Lang, 1987*). The ice surface slope controls potentiometric surfaces, generally guiding subglacial water flow parallel to ice sheet surfaces (*Glen, 1952; Shreve, 1972; Fountain and Walder, 1998*).”

Lines 100-101 : I am not following. It appears I need to refer to the earlier paper. Can this be avoided by providing a bit more here?

We understand the enquiry of the reviewer to understand the scaling of the experiment without referring to the first paper presenting the experiment. We propose to add explanations on the scaling and to move this section after the description of the model (cf. new section 2.3. “Scaling and limitations”):

“Considering that meltwater is here simulated by an injection of water, the rules of a classical scaling where the model is a miniaturisation of nature are not practical (*Paola et al., 2009*). Subglacial water drainage is generally controlled by fluctuations in locations of ice sheet margins. Similarly, in our experiments, the silicon putty margin controls the water pressure gradient. In this perspective, we base the scaling on the displacement of the natural ice and experimental silicon margins through time. We use a unit-free speed ratio between the silicon/ice margin velocity and the incision rate of experimental/natural tunnel valleys. The scaling is designed to ensure that the value of the ratio between margin velocity and incision rate of tunnel valleys in the experiment equals its value in natural. The projection of the minimal and maximal experimental speed ratios on the field of possible natural speed ratios highlights the field of validity of the experiments and defines the range of natural settings we can reproduce experimentally (full details in *Lelandais et al., 2016*). The main scaling limit regards the viscosity ratios between glacier ice, silicon putty and water. The size of the experimental ice stream, being partly controlled by the high silicon viscosity, may be underestimated compared to the size of modelled tunnel valleys.”

L103-106. Models at SAFL U of M often use hollow glass beads to overcome issues of density when using small models.

Producing DEM of the ice-bed interface was one of the main goal of this study and glass beads properties would have probably been less suitable for photogrammetry and 3D reconstruction (reflection problems, transparency, lack of roughness etc…). However, we think that glass beads would probably lead to the same suite of events, with a similar process of tunnel valley formation as the density of glass beads and the sand we use are similar. However the morphologies of tunnel valleys would probably differ due to changes in substratum permeability and friction coefficient.

L110-113. Comment: Having trouble visualizing where water is injected based on this description. Is water focused in one area?

The water is injected through an injector placed at the centre of the model which corresponds to the center of the silicon layer. The radial boundary of the silicon layer provide a radial flow of water so water is not constrained to flow in only one direction. For the visualization the cross-sectional profile in the Figure 1 show how water is injected in the system.

L118. again, placement makes this feel like the first time someone suggested that rheological softening was function of strain rate, T, etc.

We suggest to modify in e.g. Bingham et al., 2010.

L119. Nor can the potentiometric surface of water within the ice.

We suggest adding another restriction to our model in this sentence. Water flow is not driven by the silicon surface slope in the experiment. We suggest to rewrite as:

“This punctual injection does not simulate the mosaic of meltwater production regions existing beneath glaciers or the episodic input from supraglacial/englacial meltwater reservoirs. Experimental meltwater routing is predominantly controlled by the water discharge we inject in our system and therefore differs from parameters controlling hydrology in glacial systems. Subglacial meltwater routing is indeed controlled by the ice surface slope, the bed topography and the glacier mass balance (*Röthlisberger and Lang, 1987*). The ice surface slope controls potentiometric surfaces, generally guiding subglacial water flow parallel to ice sheet surfaces (*Glen, 1952; Shreve, 1972; Fountain and Walder, 1998*).”

L120.: Appropriateness of reference: as I recall, he speculated and modeled that it was (based on dilatancy of layer?), but others measured it in W. Ant much more recently? Reword the way the citation is used?

We agree with the reviewer that the till influence on ice stream should be mentioned. We suggest to rewrite as follows:

“This model, designed to decipher the interaction between subglacial hydrology and ice dynamics, hinders the influence of bed topography and geology (especially the influence of subglacial till) (*Winsborrow et al., 2010*). The deformation of the subglacial till and its complex rheological behavior is known to promote ice streaming (*Alley et al., 1987*), modify the subglacial hydrology and alter the size of tunnel valleys. The development of an analogue material scaled to reproduce subglacial till characteristics is extremely difficult so we did not try to include the equivalent of a till layer in the experiment.”

L120. Till would also change the behavior of water beneath the ice and potentially after the tunnel development

L123. and narrower tunnels

A till layer is extremely difficult to reproduce so we did no try to include one in our model. Doing so, we probably enhance some processes in the development of the ice stream and in the development of tunnel valleys. Hence we suggest to add some restrictions as follows :

“The deformation of the subglacial till and its complex rheological behavior is known to promote ice streaming (*Alley et al., 1987*), modify the subglacial hydrology and alter the size of tunnel valleys. The development of an analogue material scaled to reproduce subglacial till characteristics is extremely difficult so we did not try to include the equivalent of a till layer in the experiment. We thus assume that the velocity contrasts observed in the experiment are thus likely to be amplified in natural ice sheets, by the complex rheological behaviour of ice and till. This may lead to the development of narrower ice streams with higher relative velocities and sharper lateral shear margins in natural ice sheets than in the experiment (*Raymond, 1987; Perol et al., 2015*).”

L130. 3 levels? I don't understand and diagram doesn't help resolve.

The figure is not helpful to understand how we dispose the UV markers. Hence, we modified the figure 1 in the revised version of the manuscript to help the readers distinguishing the 3 levels of UV markers.

L130. this word helps and could be used in text. However, why this style of water injection is considered to be realistic escapes me. How could water be added to the center of an ice sheet?

The central position of the injection is specified in an earlier comment. A circular shape of the silicon layer was preferred to avoid any preliminary constraints on the water flow route and to avoid lateral boundary effects on silicon flow. This circular layer of silicon simulates only a portion of an ice sheet but not the whole ice sheet. The central injection of water is thus simulating an upstream source of water along an ice sheet portion that does not correspond to the centre of an ice sheet.

L139. Vertical? You are seeing the ice surface sink? I think that this needs to be better explained because I thought it was probably as a result of horizontal advection of "ice" and deformation of ice into a void that is formed as sediment is evacuated. But from the caption I see that it is also (primarily?) because of the water pocket forming and that the surface is elevated. The caption and figures help but the text is not clear and I have to work hard to figure out all the possibilities. Are you facing a word limit? If not, make it easier on your reader to follow experimental design and expectations.

As the injected water is pressurized, we can observe and monitor vertical displacements of the silicon surface due to water flow. We did not see the silicon sink properly but we could monitor a subsidence area when the water pocket was moving from one place to another. We propose to add the following sentence in the next section describing the UV device:

"The monitoring of every UV marker positions (in both horizontal vertical plans) through time was used to produce velocity and vertical displacement maps. Vertical displacement maps are interpolated from the subtraction of the DEM at time t with the DEM generated from the photographs taken a few seconds before the injection."

L169-170. I'd like to see photos of the setup also. These may have photo backgrounds but I cannot tell with the color overlay. Seems very idealized. Look at Ginny Catania's description of her model of subglacial drainage. Catania and Paola, 2001.

We agree with the reviewer that, in order to convince the readers who may not be familiar with such models, we should propose a better explanation of our device. Thus, we have add a picture of the device in Supplementary data. We also added a new figure in the revised version of the manuscript (Fig. 2) with six raw photographs of the main experiment stages described in figure 3.

L171-172. What is the scale of these tunnel valleys? Approximate volume of the fans? If the box is 70 cm across, how well resolved are they? I would like to see them rather than just trust the drawing.

The addition of figure 2 in the revised version with raw photographs of every stages should solve this problem. We also specify the size of every tunnel valleys and fans for every stages in the revised version of the manuscript.

<u>Specific comments – Experimental results</u>

L181-185. How long was the experiment run? How long did it take this change to occur?

L 188-189. This experiment was repeated 12 times with identical input parameters. A six-stage ice stream lifecycle linking outburst flooding transitory ice streaming and tunnel valley.

The experiment typically lasts 30 minutes (cf. Figure 3). The silicon flow pattern changes instantly when water injection starts (cf. Figure 3). We added the duration of the experiment and the information that the silicon flow pattern evolves spontaneously in response of water injection within the text as follows:

"This experiment was repeated 12 times with identical input parameters (a 30 mm-thick silicon layer of 150 mm radius; constant water input of 1.5 dm^3/h during 1800 s). After an initial identical state, a six-stage ice stream lifecycle linking outburst flooding, transitory ice streaming and tunnel valleys development has been observed for all these simulations (Fig. 3a-f, Fig. 6)."

L 197. There are earlier references that first describe and document this phenomenon: https://www.igsoc.org/journal/35/120/igs_journal_vol35_issue120_pg201-208.pdf . or https://www.cambridge.org/core/services/aop-cambridge-core/content/view/B2AD36180AEF8E3E8403A7BF2D627319/S0022143000002689a.pdf/shortterm_velocity_and_waterpressure_variations_downglacier_from_a_riegel_storglaciaren_sweden.pdf

We thank the reviewer for this reference and add it at the end of the sentence.

L 201-202. Reword. This sentence seems to be missing a word. It doesn't make sense as written.

We agree with the reviewer that this sentence is not correctly written. We suggest to modify as follows: "The lack of channels incised in the substratum indicates that water flow occurs as a distributed drainage system without any basal erosion".

L 208. What does this mean, to migrate by distributed drainage? Can you simplify and say the water pockets migrate? Are you saying that the water pockets stay at the ice-bed interface and migrate?

We agree with the reviewer and simplify the sentence as follows:

“The experiment suggests that the migration of water pockets at the ice-bed interface can contribute to the emergence of ice streams”.

L 211. What is channel scale and how does it evolve? Is water emerging from the ice margin through a narrow channel that grows headward and bifurcates?

At this stage, water is drained as a sheet flow at the silicon margin. This drainage is associated with widespread erosion, wider than the subsequent tunnel valley, producing the first low-angle fan described in supplement Figure 3. Once the water pocket drained, the water flow channelizes and a narrow valley starts forming by regressive erosion. Tunnel valleys are constantly growing along the experiment. Their size (length, width, depth) have been added for every stage.

L 212. What is the width of the head of this fan? Is it a lot broader than the fan that develops in the next stage? Need scales. I do not know of anything like this at a terrestrial margin. Till deltas off the coast of Antarctica might be of a similar scale. I wouldn't over-emphasize this since you just have sand, not till in the subsurface. I don't think that real-world ice margins leak this easily, especially where frozen. So instead you get thrust moraines from water pressure drop and tunnels.

The width of the head of every fan have been added for every stage. The first fan originating from the outburst is similar to the fan developing afterward apart from the angle. Indeed the first fan is a low-angle fan and the subsequent fan developing with tunnel valley is a high-angle fan. Although both fans are similar in size, the first one originating from the outburst flood forms nearly instantly, however the second one forms progressively during tunnel valley development.

L 213-216. I would expect the ice stream to evolve immediately prior to the tunnel valley formation. Why decreasing basal water pressure lead to it? Are you sure ice stream isn't when bubble reaches margin, immediately prior to TV formation? How long is all this taking and can you really resolve it? Are you slowing down the cameras? Is it video? Stop motion photography?

Silicon flow is progressively accelerating during migration of the water pocket. Obviously, the silicon flow is high when the water pocket reaches the margin but we record a peak velocity when the water pocket drains. We use a system of 7 cameras with a 5 second delay, but to be sure of our results we ran some experiments with a 1 second delay to visualize and validate the process described in the text.

L 219. Comments: e.g. Kamb? Bering Glacier surge and outburst is well documented.

As pointed out by the second reviewer this reference is not the best fit to support our result so we decide to choose Anderson et al. (2005) who documented ice flow acceleration triggered by outburst flooding.

L 221. Magnusson et al., 2007

We suggest to add e.g. before the reference

L 226-227. What is their scale in the experiment? How do they scale with the ice streams?

We agree with the reviewer that the figure itself is not sufficient to estimate the dimensions of our tunnel valleys. Consequently, we added tunnel valleys sizes at every stage in the manuscript. Compared to nature, experimental tunnel valleys are disproportionate compared to the ice stream size. The model itself constrains the size of the ice stream. The disproportion could also be the consequence of the analogue material we use in the experimental setup. The silicon putty is way too viscous to be scaled to glacier ice (this is clearly mentioned in the text). Using a less viscous material, the ice stream would have probably been wider and more scaled to tunnel valley size. However, silicon was selected as it shares some essential characteristics with glacier ice and mainly because its perfect transparency allows DEMs of the silicon-bed interface to be reconstructed.

L 227-228. I would like to see a cleaner description of model observations because here it appears that interpretations and discussion are interwoven.

We have choose this organization which alternates description of the model and natural examples, directly after the description of every stage, in order 1- to validate each experimental observations by natural examples, 2- to avoids many repetitions in the manuscript to facilitates the reading. We wanted to base the main discussion on more general and global implications of our modelling results.

L 230 . What is the width at the head of the fan? Is it the width of the tunnel?

We added sizes of tunnel valleys and fans for every stage in the results part. As silicon flows, the silicon layer progressively pushes the fan so the width at the head of the fan is wider than the width of the tunnel valley.

L 249. and that eskers formed in tunnel valleys represent a waning flow stage.

It is true that eskers within tunnel valleys symbolize a decrease in water flow velocity. Hence, they might represent the ultimate stage of tunnel valley development. However, we cannot simulate this final deposition stage in our experiment.

L 259-260. We also see stagnation of the ice lobe margin. Large glaciotectonic thrust masses at ice margins are located near tunnel valley fans and seem to represent the fast flow stage immediately prior to drainage.

We thank the reviewer for this useful comment. We suggest to use these field evidence in the revised version to support our experimental results: "Large glaciotectonic thrust masses at the ice margin near tunnel valleys fans are generally assumed to be a field evidence a fast ice flow stage prior to drainage through tunnel valleys (*Hooke and Jennings, 2006*)."

L 265. I do not see field evidence of two, very different scales of floods and two styles of fan formation. I suspect that the first one you observe is more a result of the unusual way you are building water pressure beneath your ice sheet (at a single point).

The first outburst flood resulting from the first water pocket drainage is more obvious and its consequence on silicon flow is more visible (cf. Figure 3). The second outburst flood consists in the drainage of a new water pocket probably originating from the inefficiency of the first tunnel valleys to drain all water. This second water pocket is probably less significant than the first one so the consequence on the silicon is less visible. In nature if tunnel valleys originate from an outburst flood, we might not find any evidence from another catastrophic drainage as they are probably occurring in the same water path.

Specific comments – Proposed lifecycle of transitory ice streams

L 274. Are these the earliest references to this phenomenon? I think not. Use as examples or cite the foundational work.

We agree with the reviewer and add some earlier references: Bentley, 1987; Blankenship et al., 1993; Anandakrishnan et al., 1998

L 284. this is a review paper. As reviewed in Kehew and Piotrowski,

We agree with the reviewer and we suggest modifying the sentence as follows: "As reviewed in *Kehew et al. (2012)* and suggested in *Ravier et al. (2015)* this relation was suspected from the occurrence of tunnel valleys on ancient ice streams beds."

L 285-286.You may be setting up a "straw man" because I don't know how widely believed/modeled this is.

Ice streams may arise from various processes (basal decoupling, deformation of the substratum…). However most of the models, emphasizes the development of high water pressure in the bed or at the ice-bed interface. For tunnel valleys we agree that we might not be so categorical about water pressure. We suggest to modify this sentence as follows:

“However, it raised a contradiction: subglacial meltwater pressures are generally supposed to be high below ice streams (Bennett, 2003) while tunnel valleys are generally assumed to operate at lower water pressures (Marczinek and Piotrowski, 2006).”

L 288-290. I think this has been speculated before from field evidence. You may be the first to physically model it, however.

We agree with the reviewer that we might rewrite this sentence to emphasize that although several observations have already connected ice stream with outburst flood and outburst flood with tunnel valley formation we are the first to model these interactions and to propose a single model connecting outburst flooding, ice stream and tunnel valley development.

“Although speculated from field evidences, our results demonstrate that ice streaming, tunnel valley formation, release of marginal outburst floods and subglacial water drainage reorganization may be interdependent parts of a single ice stream lifecycle that involves temporal changes in subglacial meltwater pressures (Fig. 6).”

L 291-293. no comma after Approximately. But more importantly, this pocket migration is highly dependent on the focused way you introduced water into the sublacial environment. I would not make too much of it since it is highly unrealistic.

We agree with the reviewer that the way we introduce water in the model is unrealistic. However, water injection at a given discharge triggers water flow at the silicon/substratum interface. The consequences on silicon flow should be comparable to the influence of subglacial meltwater on ice flow dynamics and therefore not be so unrealistic.

L 297-300. Why would they switch on precisely when water drains? How do ice streams migrate headward in this scenario? I think the ice stream migration timescale is very different than the water drainage timescale. You refer to timescales in a vague way in the beginning of the paper. Time to return to those ideas?

In our experiment, we define the ice stream birth phase when a corridor of high silicon flow appears. Before, the silicon flow velocity only increases above the migrating water pocket. Using a more viscous material than glacier ice has a consequence on timescale involved in ice stream migration. . The silicon putty accelerates the process of ice streaming and we cannot observe the headward migration of the ice stream. The migration of the experimental ice stream in response to re-routing of the water occurs almost instantaneously. Once more, this very quick migration may be a consequence of the high viscosity of the silicon we use during modelling.

L 309-310. in contrast, we see ice stream locations and tunnel systems becoming fixed. Tunnels are reoccupied again and again as an ice sheet retreats.I'm not saying that ice streams dont' migrate, just at a different time scale (or again, this might be an artifact of the way you are introducing water.)

Our study only proposes an alternative solution for ice stream migration and lateral development of tunnel valley, based on meltwater re-routing. If we consider that tunnel valley development occurs progressively, the drainage can be inefficient, possibly leading to meltwater storage. The drainage of stored meltwater could trigger a second phase of ice flow acceleration. If drainage occurs laterally to the main drainage path represented by the pre-existing tunnel valley system, drainage may indeed trigger a lateral migration of the ice stream path and the formation of a new tunnel valley (as observed in our experiment; Fig. 3). Of course, this drainage could also occur within the pre-existing tunnel valley system, thus not modifying the position of the ice stream path.

L 324-327. This seems to be taking the results of the experiment a bit far and a slightly misrepresenting the conclusions (or at least the dire nature of them) of these papers.

We agree with the reviewer that we might have over-interpreted the references we used. We propose to rewrite this sentence as follows: “This further suggest that tunnel valley development could secure ice sheet stability as hinted by Marczinek and Piotrowski. (2006) by preventing catastrophic ice stream collapses”.

L 328. a slash is not proper punctuation (a pet peeve).

We suggest to rewrite as :

“In a global change context, phenomena of ice stream stabilisation would requires that pre-existing and newly forming tunnel valleys systems expand sufficiently fast to accommodate increased meltwater production.”

L 329-332 : Comment : You may have needed to make the conclusions seem relevant to a broad audience but to readers of The Cryosphere, this seems a bit extreme and sensational.

We agree with the reviewer that the current conclusion is a bit extreme and focused on current global warming issues. We deleted the “sensational” part of the conclusion in the revised version of the manuscript.

L 335-336. This schematic is fine as long as we understand it is an interpretation. I'd like the original model results to look more "real" like photos of a model, and less like this.

This schematic is actually an interpretation of the six-stages ice stream lifecycle we describe in the manuscript, based on true experimental data. This interpretative sketch is actually drawn using experimental DEM of the bed and flow velocity maps of the silicon. We just additionally drew an ice column and fans to the experimental data to obtain a practical model, easier to compare with nature. We decided to mix interpretational and experimental data in this final diagram of the manuscript to constitute a synthetic model, easy to understand and usable for any glacial geologists or glaciologists. We already added in the revised version a figure (Fig. 2) displaying “real” photo of the experiment that will help the reader to better apprehend the model.

Referee #2 : Anonymous reviewer

General comments

This paper describes an analog experimental model for ice flow over sediments and water, and uses the results of the experiments to describe a transitory lifecycle of an ice stream. The paper is short; it identifies some of the known features of modern and paleo ice streams, discusses the combination of conditions that are thought to play a role in the dynamics of ice streams, describes the experimental setup, the results of an experiment, and the inferred ‘lifecycle’ behaviour of an ice stream. The experimental approach is quite novel (though not without precedent; notably the paper of Catania & Paola (2001) is absent from the references and deserves comment) and I think it is welcome. You might also reference the laboratory work of Kowal & Worster (2015), which has some similar results. The setup appears to be quite sophisticated, allowing detailed mapping of elevation changes and velocities. There therefore appears to be considerable scope with this approach. However, the current manuscript is somewhat lacking in detail and I think there needs to be more scientific discussion about the extent to which the experiment does and does not represent the real world. There also is relatively little data presented on the detailed measurements that have evidently been taken. At present, it reads like a re-hash of a submission to Nature, and I think it needs a bit of expansion to fill in some details for the more discerning reader. The paper is nevertheless well written and interesting, and I think with improvements it can be a valuable contribution to the literature.

As pointed out by both reviewers, we agree that the current version is lacking some data especially on tunnel valleys size and a section specifically dedicated to discuss the limitations of this model. This model do not and cannot simulate the whole complexity of a natural system, we therefore added some clarifications throughout the manuscript (cf. replies to referee 1's comments) on how this model works but also on how some of the experimental parameters can potentially alter the model validity.

Specific comments:

The experimental approach is advocated partly on the basis that numerical modelling and field observations are not able to include all the coupled components of the ice stream, sediment, water system. However, there is almost no discussion given to the drawbacks of an experimental approach; in particular, the issues of things that are missing (the analog 'ice' does not change phase for example), and the extent to which the processes can be scaled down. There should be more attention given to this. For example, what is the Reynolds number of the subglacial water flow? Are the dimensions of the 'tunnel valleys' that form comparable to real tunnel valleys (relative to ice thickness, say), and does the grain size of the sand not have some effect.

We agree with the reviewer that the lack of discussion on the drawbacks of an experimental approach is an issue. We suggest to add a section within the methods to mention the process that are not simulated in the model (cf. section, 2.3. "Scaling and limitations").

How was the flow-rate of water to be injected chosen, and are the results sensitive to this? Is it realistic? (In terms of water flux as compared to ice flux, say). How is it decided when to start injecting the water? Does this make a difference?

The flow rate of water is calculated so that water pressure is exceeding the combined weight of the silicon and sand layers. This is calculated beforehand to initiate water flow at the silicon-bed interface. The flow rate of water is not realistic against the silicon flux because it would require a perfect scaling which is impossible from a material point of view. We added these details in the methods part of the revised version of the manuscript:

"Water discharge is calculated beforehand so that water pressure exceeds the combined weight of the sand and silicon layers. The injection of water starts when the silicon layer reaches the dimensions we fixed for every experiment (15 cm radius and 3 cm thickness) and a perfect transparency. Once injected, water flow is divided into a Darcy flow within the substratum and a flow at the silicon/substratum interface. The water flowing at the silicon/substratum interface originates from a pipe forming at the injector once water pressure exceeds the cumulative pressure of the silicon and sand layers. The ratio between the Darcy flow and the flow at the silicon/substratum interface is inferred from computations of the water discharge flowing through the pipe based on the substratum properties and the input discharge. We estimate that 75% of the input discharge is transferred as Darcy flow in the substratum and 25% of the input discharge along the silicon/substratum interface."

How much of the water flow is through the permeable sediments and how much in a film at the sediment/silicon interface? How thick is the water layer? Are the sediments in suspension or carried as bedload?

We have estimated that 75% of the water is flowing through the permeable sediments and 25% at the interface. This ratio have been inferred from computations of the water flowing through the pipe forming over the injector. We add these details in the methods part (See the modifications to answer the last comment). Water layer thickness (over a 1 mm inside the water pocket) can be inferred from the vertical uplift maps in Figure 3.

Only one particular experiment is described in any detail. It is not clear how repeatable this is except for the comment on l190 that the observed lifecycle is the same for 12 identical runs; but it is hard to imagine that the development of the three ‘tunnel valleys’ is exactly the same each time. Is there really always two stages of streaming? Do they always appear on the same sides of the experiment? How different are the plots in figure 3 between different experiments (in terms of peak velocity for example)? There should be more discussion of the other experiments.

We agree that it might be confusing to state that every experiment leads to the same outcome. It is true that every experiment lead to the development, migration and drainage of a water pocket that subsequently trigger ice streaming. For every experiment, the drainage phase is followed by the development of tunnel valleys that causes ice stream deceleration. However, there is variability in the amount and size of tunnel valleys we form between the different experiments. We also notice that there is not always a lateral migration of the ice stream when the drainage efficiency of the tunnel valley system is sufficiently high to prevent storage/drainage of a second water pocket.
A new paragraph (section 3.2 “Experimental reproducibility and variability”) discussing the range of experimental results has been added to the revised version of the manuscript.

Figure 2. It is not completely clear what is shown in the first column, and the color scale chosen is not particularly suited to showing elevation changes (e.g. it is quite unclear where zero is). Given that there are negative values, this is presumably an elevation change from some reference? What is taken as the reference, given that the silicon is anyway spreading (and presumably lowering?) before injection starts?

The surface elevation maps are made from a reference picture taken just before the injection (few seconds before the injection). We suggest to add the 0 on the color scale for the vertical displacement maps and to add information on how silicon flow velocities and elevation map are interpolated within the methods section:

“The monitoring of every UV marker positions (in both horizontal vertical plans) through time was used to produce velocity and vertical displacement maps. Vertical displacement maps are interpolated from the subtraction of the DEM at time t with the DEM generated from the photographs taken a few seconds before the injection. Velocity maps are interpolated from the subtraction of the position of every marker at time t with the position of the same markers at the previous stage.”

The surge of the Variegated glacier referenced on line 219 was, as I understand it, accompanied by a decrease in the outlet discharge of subglacial water rather than an increase. A subsequent increase in discharge, with the development of a more efficient drainage system, accompanied the termination of the surge. So I am not sure this is quite the same behaviour as seen in your experiments.

We agree with the reviewer that the study of Kamb (1985) on the Variegated glacier is not the best fit to compare with our results as the surge termination is associated with an outburst flood. We suggest to switch this reference with the study of Anderson et al., 2005 which observe and measure an ice flow acceleration following the outburst flood of the Hidden Creek Lake, Alaska.

The slow-down of the ice stream is attributed to a lowering of subglacial water pressure together with the growth of tunnel valleys, but presumably in the experiments there is also an influence of the changing silicon geometry which is driving the silicon flow. The surface is lowered over the central part of the dome and the driving stress is therefore reduced. What is the evidence that the ageing of the ice stream is not simply due to this effect? (which is also present in the real ice-stream problem too).

Broadly speaking it is true that the change of silicon geometry will inevitably slow down the silicon flow as the amount of silicon which is available to flow progressively decreases. However, we described an experiment where all processes of ice streaming and tunnel valley formation occur in a short period of time (30 min). Hence, the progressive decay of the ice stream related to ice thinning is negligible here. However, if we consider a context where the silicon layer thins significantly, water pressure would decrease similarly to nature. Indeed, the size of the pipe forming when we inject water within the substratum is dependent on the thickness of the sand and silicon layers. Hence, if the silicon layer thickness decreases the pipe circumference would significantly increase, which conduct to an increase of the water discharge flowing at the substratum/interface and a decrease of water pressure. Consequently, the stagnation of the ice stream in our 12 experiments is always achieved despite an increase of water flow at the silicon/substratum interface.

Modelled subglacial floods and tunnel valleys control the lifecycle of transitory ice streams

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Ice streams are corridors of fast-flowing ice that control mass transfers from continental ice sheets to oceans. Their flow speeds are known to accelerate and decelerate, their activity to switch on and off, and even their locations to shift entirely. Our analogue physical experiments reveal that a lifecycle incorporating evolving subglacial meltwater routing and bed erosion can govern this complex transitory behaviour. The modelled ice streams switch on and accelerate when subglacial water pockets drain as marginal outburst floods (basal decoupling). Then they decelerate when the lubricating water drainage system sponteanously organising itself into channels that create tunnel valleys (partial basal recoupling)~~as basal coupling increases as a consequence of the lubricating water drainage system spontaneously organising itself into channels that erode tunnel valleys~~. The ice streams~~ey~~ surge or jump in location when these water drainage systems maintain low discharge but they ultimately switch off when tunnel valleys have expanded to develop efficient drainage systems. Beyond reconciling previously disconnected observations of modern and ancient ice streams into a single lifecycle, the modelling suggests that tunnel valley development may be crucial in stabilising portions of ice sheets during periods of climate change.

Keywords: ice streams, experimental modelling, subglacial meltwater drainage, tunnel valleys, subglacial outburst floods

1. Introduction

Continental ice sheets currently store the equivalent of a 65 m thick global equivalent water layer and have been major contributors to the nearly 85 mm global sea level rise measured between 1993 and 2017 (*Vaughan et al., 2013; Beckley et al., 2015*). The mass transfer from these ice sheets to the ocean is spatially heterogeneous: approximately 80% of the ice discharge is focused in a finite number of ice streams, which act as preferential drainage pathways for meltwater and sediment also (*Bamber et al., 2000; Bennett, 2003*).

Modern and ~~palaeo~~ ancient ice streams are typically hundreds of kilometres long and a few kilometres to tens of kilometres wide, with ice velocities of the order 10^2 to 10^4 m/~~.~~yr~~$^{-1}$~~. They occur in all known ice sheets, but why and where they initiate, and the controls on their dynamics remain debated. Numerical modelling suggests that ice flow might self-organise into regularly-spaced ice streams as a consequence of thermomechanical feedbacks within ice (*Payne and Dongelmans, 1997; Hindmarsh, 2009*) or because of inherent instability of thin subglacial meltwater films (*Kyrke-Smith et al., 2014*). Numerous observations however, have highlighted preferential location of ice streams at sites of specific bed properties such as in topographic troughs, over areas of soft sedimentary geology, zones of higher geothermal heat flux or as a consequence of where subglacial meltwater is routed (*Winsborrow et al., 2010; Kleiner et al., 2014*). These viewpoints might not be mutually exclusive if self-organisation into regularly-spaced streams is the primary control but that it is strongly mediated by local bed templates (e.g. troughs) or events (meltwater drainage) that initiate or anchor streams in certain locations. Exploring this hypothesis by numerical modelling has not yet been achieved because of uncertainties in how to formulate basal ice flow in relation to bed friction, and due to challenges of including all potentially relevant processes, especially so for subglacial water flow (*Flowers, 2015*).

Observations of spatial and temporal variations in the activity of ice streams against fluctuations in their subglacial hydrology suggest that the style and flux of water drainage is a major component driving change. Examples include: reorganisation of subglacial drainage systems (*Elsworth and Suckale, 2016*), subglacial water piracy (*Vaughan et al., 2008; Carter et al., 2013*), and development and migration of transient subglacial water pockets (*Gray et al., 2005; Peters et al., 2007; Siegfried et al., 2016*). However, these relations have been observed or inferred independently, at different places and on yearly timescales, thus limiting our understanding of the true role of the subglacial hydrology as ~~them of them as~~ primary drivers or secondary drivers of ice stream changes~~as more minor effects of change~~. In this paper, we circumvent the challenge of numerically modelling ice stream initiation and dynamics, including subglacial water drainage, by exploiting a physical laboratory approach that simultaneously combines ice flow, water drainage and bed erosion.

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Connections between ice stream activity and subglacial hydrology are supported by the occurrence of geomorphic markers of meltwater drainage on ancient~~palaeo~~ ice stream beds (e.g. meltwater channels, tunnel valleys, eskers) (*Margold et al., 2015; Livingstone et al., 2016; Patterson, 1997*). Among these landforms, tunnel valleys deserve specific attention because they have high discharge capacities and, as such, may be major contributors to the release of meltwater and sediment to the ocean; they may also promote ice sheet stability by reducing the lubricating effect of high basal water pressure. These~~unnel~~ valleys are elongated and over-deepened hollows, ranging from a few kilometres~~up~~ to hundreds of kilometres long, from hundreds metres to several kilometres wide and from meters to hundreds of meters deep. Their initiation~~formation~~ is generally attributed to subglacial meltwater erosion but ~~there is still no consensus on~~ their development processes (in time and space) and on their relationship to ice streaming are still debated. Indeed, ice streams commonly operate because of high basal water pressure while the development of a tunnel valleys system generally leads to enhances drainage efficiency and basal water pressure reduction (*Engelhardt et al., 1990; Kyrke-Smith et al., 2014; Marczinek and Piotrowski, 2006*).~~A conundrum being that ice streams appear to require high water pressure while tunnel valleys are believed to involve low water pressure (*Marczinek and Piotrowski, 2006*).~~

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Several field studies have already suggested a connection between catastrophic glacial outburst floods at ice sheet margins and a suite of events involving ice streaming, tunnel valleys development and stagnation of the ice margin (*Bell et al., 2007; Hooke and Jennings, 2006; Jørgensen and Piotrowski, 2003; Alley et al., 2006*). ~~Ice streaming and tunnel valley development are both suspected to be linked to the release of catastrophic glacial outburst floods at ice sheet margins (*Bell et al., 2007; Hooke and Jennings, 2006; Jørgensen and Piotrowski, 2003; Alley et al., 2006*).~~ Such outburst floods can profoundly and rapidly alter the oceanic environment by transferring considerable amounts of ice, freshwater and sediment from continents to oceans (*Evatt et al., 2006*). The suspected connection between ice streams, tunnel valleys and outburst floods has never been observed or modelled however.

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Here, we describe the results of a physical experiment performed with an innovative analogue modelling device that provides simultaneous constraints on ice flow, subglacial meltwater drainage, subglacial sediment transport and subglacial landform development (*Lelandais et al., 2016*; Fig. 1). We propose that the location and initiation of ice streams might arise from subglacial meltwater pocket migration and drainage pathways and that the evolution of ice stream dynamics is latter controlled by subglacial drainage reorganization and tunnel valleys development. ~~From these results, we infer that ice streaming, subglacial meltwater pocket migration, subglacial drainage reorganisation, tunnel valley formation and glacial outburst floods are linked in influencing the location and dynamics of ice streams.~~ This study reconciles into a single story several detached inferences, derived from observations at different timescales and at different places on modern and ancient ice streams.

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2. Experimental ice stream model

Ice stream dynamics are controlled by various processes that act at different space and time scales; they also involve several components with complex thermo-mechanical behaviours (ice, water, till, bedrock) (*Paterson, 1994*). Considering all these processes and components simultaneously, together with processes of subglacial erosion, is thus a challenge for numerical ~~modelling, especially with numerical~~ computational ~~means~~ modelling (*Fowler and Johnson, 1995; Marshall, 2005; Bingham et al., 2010*). Based on this statement, some attempts in analogue modelling have been made to improve our knowledge on subglacial erosional processes by meltwater (*Catania and Paola, 2001*) or gravity current instabilities produced by lubrication (*Kowal and Worster, 2015*). To combine ice flow dynamics and erosional aspects in a single model, we designed an alternative experimental approach that allows simultaneous modelling of ice flow, subglacial hydrology and sedimentary/geomorphic processes. ~~To overcome partly this issue, we use an alternative experimental approach that allows simultaneous modelling of ice flow, subglacial hydrology and sedimentary/geomorphic processes in a portion of an ice sheet (*Paola et al., 2009*).~~ With all the precautions of use inherent of analogue modelling, our experiments reproduce morphologies and dynamics that compare well with subglacial landforms and ice stream dynamics despite some differences of spatial and time scales and a number of active processes (e.g. *Paola et al., 2009*).~~Potentiometric surfaces that control subglacial water flow are generally parallel to ice sheet surfaces (*Fountain and Walder, 1998*). Subglacial water drainage is thus controlled by fluctuations in locations of ice sheet margins. The scaling of the experiment is based on this rule and is designed to ensure~~

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~~that the value of the ratio between margin velocity and incision rate of tunnel valleys in the experiment equals its value in natural systems (cf. *Lelandais et al., 2016* for scaling details).~~

2.1.Experimental apparatus

The model is set in a glass box (70 cm long, 70 cm wide and 5 cm deep) (Fig. 1). A 5 cm thick, flat, horizontal, permeable and erodible substratum, made of sand (d_{50}=100 µm) saturated with pure water and compacted to ensure homogeneous values for its density (ρ_{bulk} = 2000 kg.m^{-3}), porosity (Φ = 41 %) and permeability (K = 10^{-4} m/~~.~~s~~$^{-1}$~~), rests on the box floor. The ice sheet portion is modelled with a 3 cm thick layer of viscous (η = $5{\cdot}10^4$ Pa.s) and transparent but refractive (n = 1.47) silicon putty placed on the substratum. The model is not designed to simulate an entire ice sheet; it is circular in plan view (radius = 15 cm) however, to avoid lateral boundary effects on silicon flow. Subglacial meltwater production is simulated by injection of water with a punctual injector, 4 mm in radius, placed at a depth of 1.8 cm in the substratum, and connected to a pump (Fig. 1). The injector is located below the centre of the silicon layer to be consistent with the circular geometry of the experiment. The water discharge is constant (1.5 dm^3/h) over the duration of the experiment and generates water flow at the silicon-substratum interface and within the substratum. Water discharge is calculated beforehand so that water pressure exceeds the combined weight of the sand and silicon layers. The injection of water starts when the silicon layer reaches the dimensions we fixed for every experiment (15 cm radius and 3 cm thickness) and a perfect transparency. Once injected, water flow is divided into a Darcy flow within the substratum and a flow at the silicon/substratum interface. The water flowing at the silicon/substratum interface originates from a pipe forming at the injector once water pressure exceeds the cumulative pressure of the silicon and sand layers. The ratio between the Darcy flow and the flow at the silicon/substratum interface is inferred from computations of the water discharge flowing through the pipe based on the substratum properties and the input discharge. We estimate that 75% of the input discharge is transferred as Darcy flow in the substratum and 25% of the input discharge along the silicon/substratum interface.

2.2.Acquisition process and post-processing

In order to monitor the development of landforms on the substratum, we use six synchronised cameras equidistant from the experiment centre (Fig. 1) taking photographs of the experiment every 5 seconds. Two cameras (orange on Fig. 1) cover the whole extent of the experiment and four cameras (blue on Fig. 1) focus on specific regions to obtain higher resolution images. These cameras take simultaneous pictures with differing positions and orientations. Digital elevation models of the silicon surface and of the substratum are derived from these images by photogrammetry. The ultimate stage of the experiment is to remove distortions due to light refraction through the silicon putty and apply corrections to the substratum topography. This treatment is achieved using a custom algorithm able to evaluate the gap between the measured altitude and the real altitude of each pixel of the DEM (cf detailed post-treatment methods in *Lelandais et al., 2016*). Tests performed on previously known topographies show that the vertical precision of the retrieved digital elevation models is better than 10^{-1} mm.

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The flow velocity of the silicon layer is monitored near its base (V_{base}), at mid-depth (V_{mid}) and at its surface ($V_{surface}$), with an additional camera placed over the centre of the experiment (green on Fig. 1). For that purpose, the camera records the position on pictures taken at regular time intervals in ultraviolet (UV) of 180 UV paint drops (1 mm in radius) placed at 1 mm above the base, at mid-depth and at the surface of the silicon layer (Fig. 1 and Fig. S1). The monitoring of every UV marker positions (in both horizontal vertical plans) through time was used to produce velocity and vertical displacement maps. Vertical displacement maps are interpolated from the subtraction of the DEM at time t with the DEM generated from the photographs taken a few seconds before the injection. Velocity maps are interpolated from the subtraction of the position of every marker at time t with the position of the same markers at the previous stage. These passive markers are transparent at visible wavelengths and do not alter pictures of the substratum taken through the silicon cap. They represent less than 0.5% of the silicon layer in volume and tests have shown that they do not affect its overall rheological behaviour. Uncertainties in the measured position of markers on images are less than one pixel in size (i.e. less than10^{-1} mm), thus uncertainties in the derived velocities are comprised between $5{\cdot}10^{-4}$ and $2{\cdot}10^{-3}$ mm/s, depending on the time interval between photographs.

2.3.Scaling and limitations

Considering that meltwater is here simulated by an injection of water, the rules of a classical scaling where the model is a miniaturisation of nature are not practical (*Paola et al., 2009*). Subglacial water drainage is generally controlled by fluctuations in locations of ice sheet margins. Similarly, in our experiments, the silicon putty margin controls the water pressure gradient. In this perspective, we base the scaling on the displacement of the natural ice and experimental silicon margins through time. We use a unit-free speed ratio between the silicon/ice margin velocity and the incision rate of experimental/natural tunnel valleys. The scaling is designed to ensure that the value of the ratio between margin velocity and incision rate of tunnel valleys in the experiment equals its value in natural. The projection of the minimal and maximal experimental speed ratios on the field of possible natural speed ratios highlights the field of validity of the experiments and defines the range of natural settings we can reproduce experimentally (full details in *Lelandais et al., 2016*). The main scaling limit regards the viscosity ratios between glacier ice, silicon putty and water. The size of the experimental ice stream, being partly controlled by the high silicon viscosity, may be underestimated compared to the size of modelled tunnel valleys.

Considering that our model is a simplification of nature, we cannot simulate its whole complexity. In contrast with ice, the commercial silicon putty we use (Dow Corning, SGM36) is impermeable, newtonian, isotropic, its viscosity is nearly independent of temperature between 10 and 30°C. Therefore, rheological softening of ice with strain rate, temperature, anisotropy and meltwater content (e.g. *Bingham et al., 2010*) cannot be fully reproduced. The silicon putty cannot reproduce the ice/water phase transition, supporting the use of punctual water injection in the experiment. This punctual injection does not simulate the mosaic of meltwater production regions existing beneath glaciers or the episodic input from supraglacial/englacial meltwater reservoirs. Experimental meltwater routing is predominantly controlled by the water discharge we inject in our system and therefore differs from parameters controlling hydrology in glacial systems. Subglacial meltwater routing is indeed controlled by

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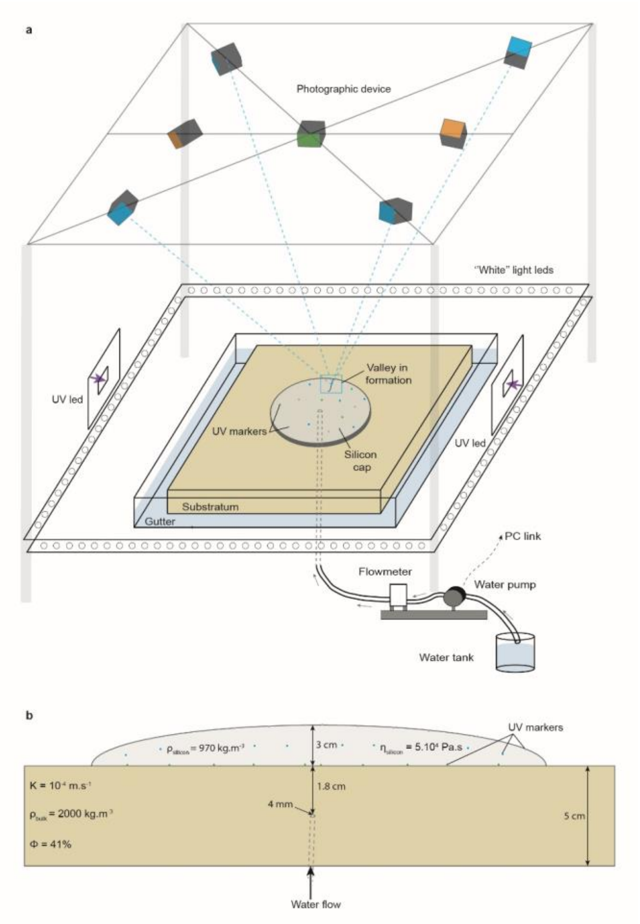
Mis en forme : Normal, Sans numérotation ni puces the ice surface slope, the bed topography and the glacier mass balance (*Röthlisberger and Lang, 1987*). The ice surface slope controls potentiometric surfaces, generally guiding subglacial water flow parallel to ice sheet surfaces (*Glen, 1952; Shreve, 1972; Fountain and Walder, 1998*). Finally, the substratum we use is homogeneous, flat and composed of a well-sorted mixture of sand-sized grains. This model, designed to decipher the interaction between subglacial hydrology and ice dynamics, hinders the influence of bed topography and geology (especially the influence of subglacial till) (*Winsborrow et al., 2010*). The deformation of the subglacial till and its complex rheological behavior is known to promote ice streaming (*Alley et al., 1987*), modify the subglacial hydrology and alter the size of tunnel valleys. The development of an analogue material scaled to reproduce subglacial till characteristics is extremely difficult so we did not try to include the equivalent of a till layer in the experiment. We thus assume that the velocity contrasts observed in the experiment are thus likely to be amplified in natural ice sheets, by the complex rheological behaviour of ice and till. This may lead to the development of narrower ice streams with higher relative velocities and sharper lateral shear margins in natural ice sheets than in the experiment (*Raymond, 1987; Perol et al., 2015*).

~~In contrast with ice, the commercial silicon putty we use (Dow Corning, SGM36) is impermeable, Newtonian, isotropic, and its viscosity is nearly independent of temperature between 10 and 30°C. Therefore, rheological softening of ice with strain rate, temperature, anisotropy and meltwater content (*Bingham et al., 2010*) cannot be reproduced. We did not try to include the equivalent of a till layer in the experiment, although till deformation is known to promote ice streaming (*Alley et al., 1987*). The velocity contrasts observed in the experiment are thus likely to be amplified, in natural ice sheets, by the complex rheological behaviour of ice and till. This may lead to the development of narrower ice streams with higher relative velocities and sharper lateral shear margins in natural ice sheets than in the experiment (*Raymond, 1987; Perol et al., 2015*).~~


a
Photographic device
"White" light leds
UV led
Valley in formation
UV markers
Silicon cap
UV led
Substratum
Gutter
PC link
Flowmeter
Water pump
Water tank
b
UV markers
ρsilicon = 970 kg.m-3
3 cm
ηsilicon = 5.104 Pa.s
K = 10-4 m.s-1
1.8 cm
4 mm
ρbulk = 2000 kg.m-3
5 cm
Φ = 41%
Water flow

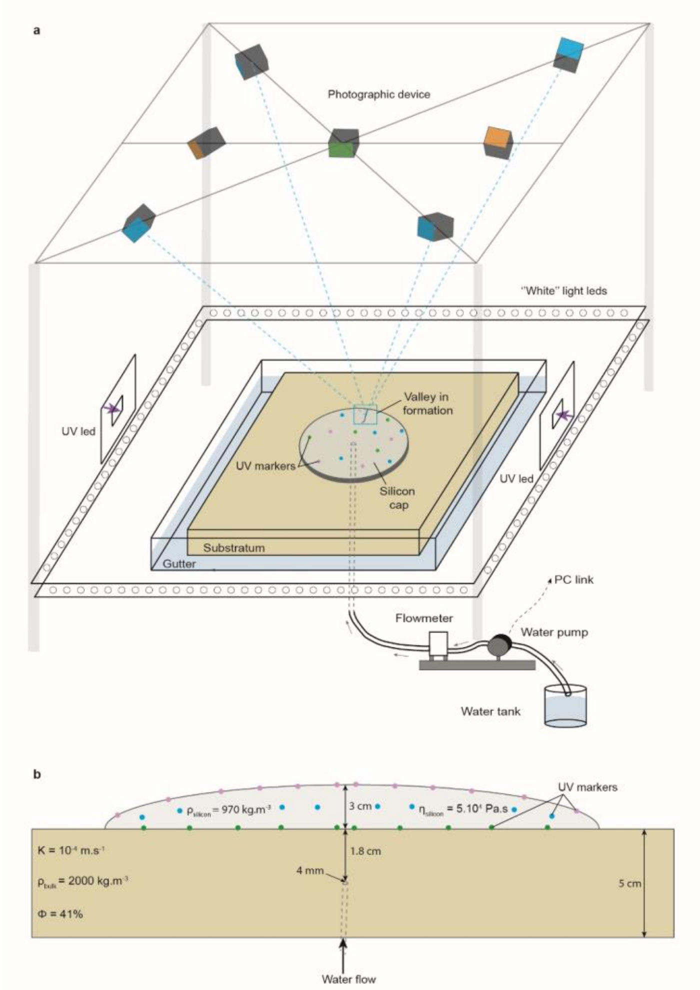


Figure 1. Description of the analogue device used in this study. a, Overview of the analogue device. The analogue device consists in a 70 cm long, 70 cm wide and 5 cm deep glass box filled with saturated and compacted sand simulating the substratum. The ice sheet portion is simulated by a circular layer of silicon putty containing 3 levels of UV markers. Meltwater production is simulated by a central and punctual injection of pure water within the substratum. Five synchronized cameras placed above the silicon putty (in blue) focus on the tunnel valley system and are used to produce digital elevation models by photogrammetry. Another camera (in orange) takes overview photographs of the analog device to follow the progress of the whole experiment. A last camera (in green) is positioned at the vertical of the silicon layer centre and is configured to take high-resolution photographs in black light of the UV markers (illuminated with two lateral UV led lights). b, Cross-sectional profile of the analogue device displaying the position of the UV markers and the physical characteristics of both the substratum and the silicon layer.

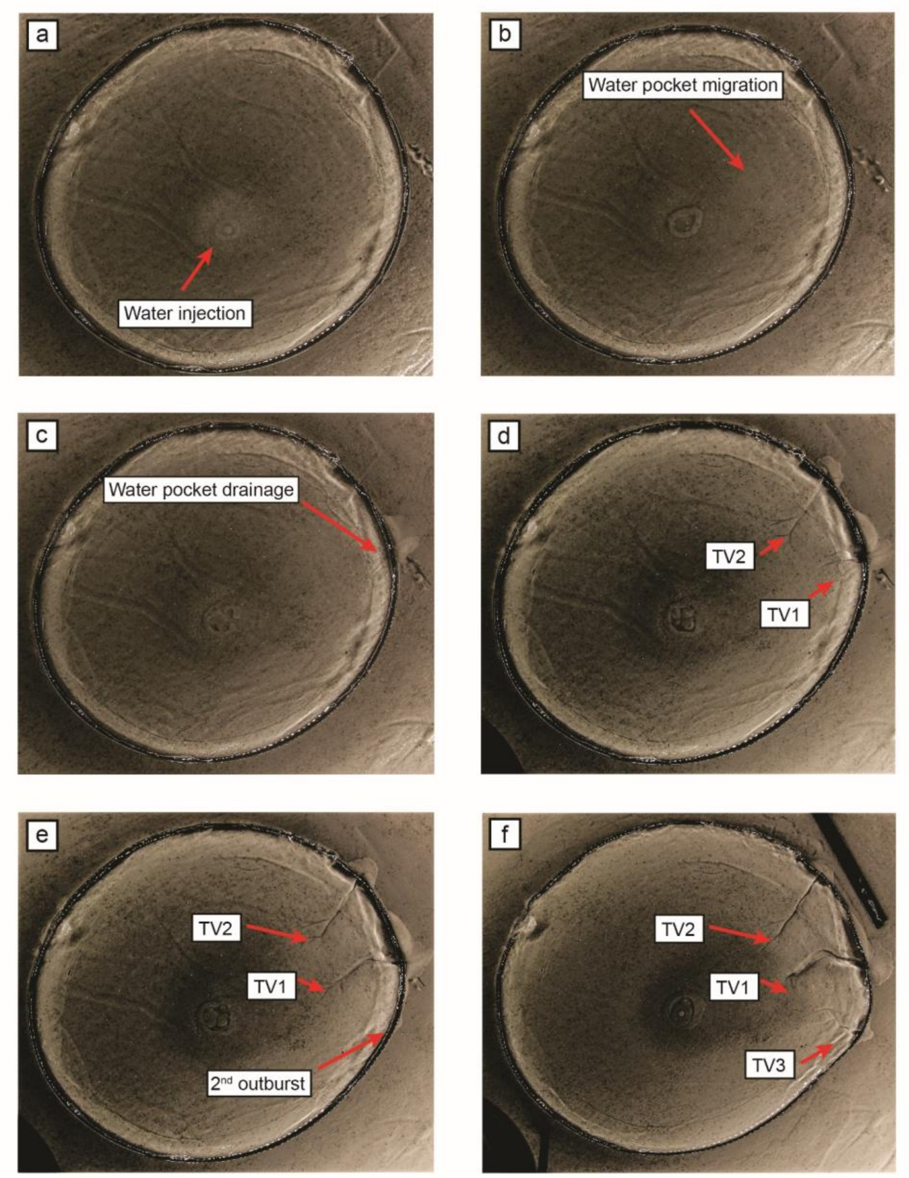


Figure 2. Temporal evolution of the experiment seen on raw photographs. a. Formation of a water pocket. b. Migration of the water pocket. c. Marginal drainage of the water pocket and onset of the silicon stream. d. Development of two tunnel valleys (TV1 and TV2). e. Drainage of a second water pocket and silicon stream migration. f. Development of a new generation of tunnel valleys (TV3) and silicon stream decay. Silicon flow velocity and silicon surface displacement maps corresponding to the six stages described here are presented in Figure 3.

3. Experimental results

3.1. Stage-by-stage experimental progress

This experiment was repeated 12 times with identical input parameters (a 30 mm-thick silicon layer of 150 mm radius; constant water input of 1.5 dm^3/h during 1800 s). After an initial identical state, a six-stage ice stream lifecycle linking outburst flooding, transitory ice streaming and tunnel valleys development has been observed for all these simulations (Fig. 3a-f, Fig. 6).

~~To monitor the vertical displacements of the silicon surface and the development of landforms on its substratum, we use six synchronised cameras equidistant from the experiment centre: two cameras (orange on Fig. 1) cover the whole extent of the experiment and four cameras (blue on Fig. 1) focus on specific regions to obtain higher resolution images. These cameras take simultaneous pictures with differing positions and orientations. Digital elevation models of the silicon surface and of the substratum are derived from these images by photogrammetry. Numerical post-treatments are performed on the digital elevation models to remove distortions of the substratum topography due to light refraction in the silicon putty (cf detailed post-treatment methods in *Lelandais et al., 2016*). Tests performed on previously known topographies show that the vertical precision of the retrieved digital elevation models is better than 10^{-1} mm.~~

~~The flow velocity of the silicon layer is monitored near its base (V_{base}), at mid-depth (V_{mid}) and at its surface ($V_{surface}$), with an additional camera placed over the centre of the experiment (green on Fig. 1). For that purpose, the camera records the horizontal position, on pictures taken at regular time intervals in ultraviolet, of 180 paint drops (1 mm in radius) placed at 1 mm above the base, at mid-depth and at the surface of the silicon layer (Fig. S1). These passive markers are transparent at visible wavelengths and do not alter pictures of the substratum taken through the silicon cap. They represent less than 0.5% of the silicon layer in volume and tests have shown that they do not affect its overall rheological behaviour. Uncertainties in the measured position of markers on images are less than one pixel in size (10^{-1} mm), thus uncertainties in the derived velocities are comprised between $5 \cdot 10^{-4}$ and $2 \cdot 10^{-3}$ mm/s, depending on the time interval between photographs.~~

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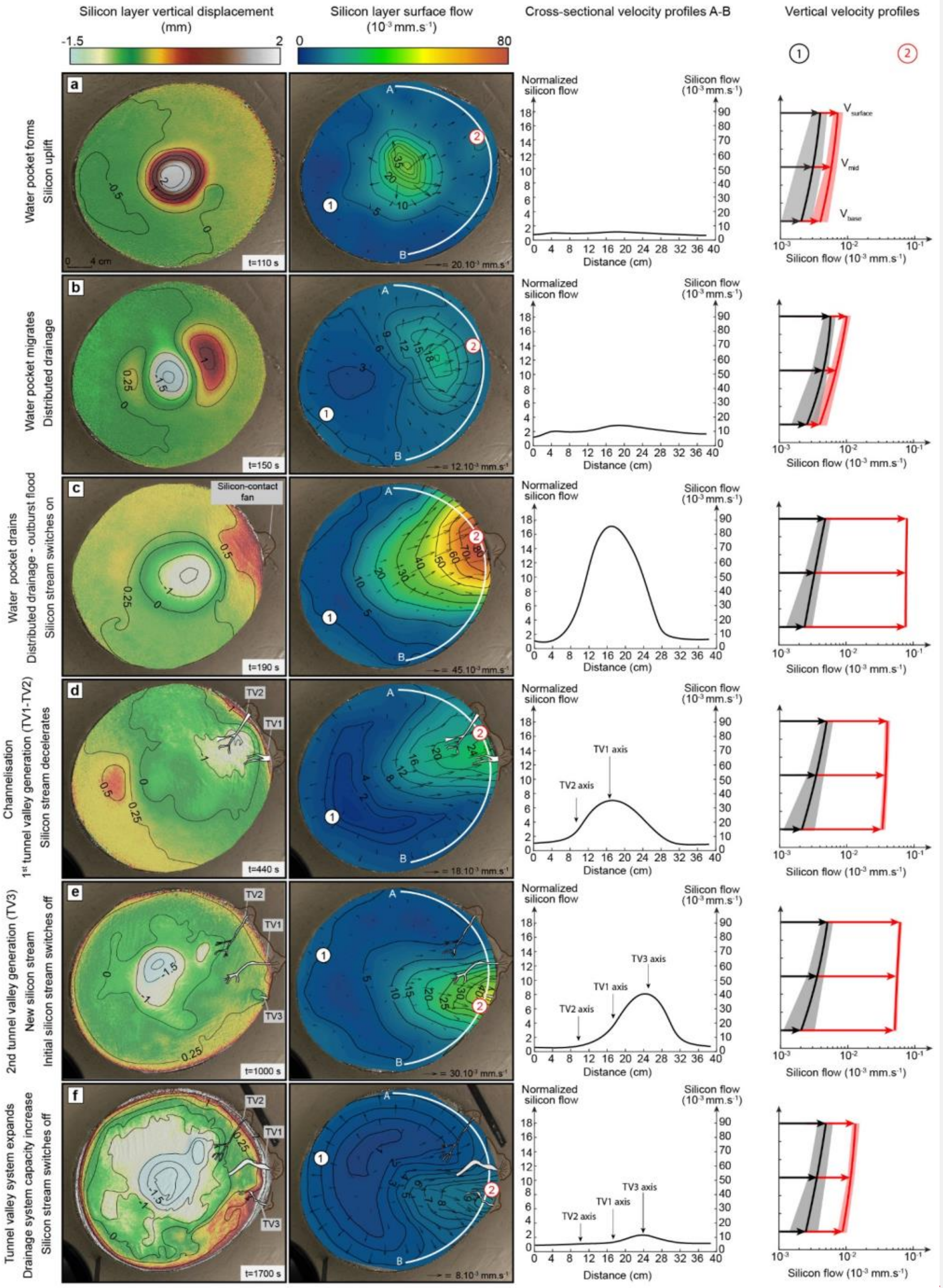
Silicon layer vertical displacement (mm)
-1.5
2
Silicon layer surface flow (10^{-3} mm.s^{-1})
0
80
Cross-sectional velocity profiles A-B
Vertical velocity profiles
1
2
a
Water pocket forms
Silicon uplift
0 4 cm
t=110 s
20.10^{-3} mm.s^{-1}
V$_{surface}$
V$_{mid}$
V$_{base}$
b
Water pocket migrates
Distributed drainage
t=150 s
12.10^{-3} mm.s^{-1}
c
Water pocket drains
Distributed drainage - outburst flood
Silicon stream switches on
Silicon-contact fan
t=190 s
45.10^{-3} mm.s^{-1}
d
Channelisation
1st tunnel valley generation (TV1-TV2)
Silicon stream decelerates
TV1
TV2
t=440 s
18.10^{-3} mm.s^{-1}
TV1 axis
TV2 axis
e
2nd tunnel valley generation (TV3)
New silicon stream
Initial silicon stream switches off
TV3
t=1000 s
30.10^{-3} mm.s^{-1}
TV3 axis
f
Tunnel valley system expands
Drainage system capacity increase
Silicon stream switches off
t=1700 s
8.10^{-3} mm.s^{-1}
A
B
Normalized silicon flow
Silicon flow (10^{-3} mm.s^{-1})
Distance (cm)
0 4 8 12 16 20 24 28 32 36 40
Silicon flow (10^{-3} mm.s^{-1})
10^{-3}
10^{-2}
10^{-1}

~~**Figure 2.** Temporal evolution of the experiment. a, Formation of water pocket, uplift of silicon surface uplift and acceleration. b, Migration of water pocket and overlying region of uplift and accelerated flow. c, Marginal drainage of water pocket and onset of silicon streaming. d, Tunnel valley development and silicon stream deceleration. e, Formation, migration and marginal drainage of a new water pocket, development of a second silicon stream and of a new tunnel valley. f, Decay of the second silicon stream. From left to right: (i) maps of vertical displacements of silicon layer surface, (ii) maps of horizontal velocity at silicon cap surface, (iii) cross sectional velocity profiles (absolute velocity on right axis, velocity normalised by background velocity on left axis, profile locations indicated by white lines A–B on maps), (iv) vertical velocity profiles for silicon stream (red profiles, locations labelled 1 on maps) and for region opposed to silicon stream (black profiles, locations labelled 2 on maps).~~

~~3. Experimental results~~

Initial state (Fig. S2). As long as no water is injected in the substratum, the silicon layer spreads under its own weight and displays the typical parabolic surface profile of an ice sheet. It increases in diameter and decreases in thickness with time, thus producing a radial pattern of horizontal velocities, which increase in magnitude from the centre ($V_{surface} < 3\cdot10^{-3}$ mm/~~·~~s~~$^{-1}$~~) to the margin ($V_{surface} = 8\cdot10^{-3}$ mm/~~·~~s~~$^{-1}$~~) (Fig. S2). V_{base} is close to 0 over the full extent of the silicon layer ($\frac{V_{base}}{V_{surface}} \sim 0\%$), indicating coupling with the substratum. The silicon flow pattern changes when meltwater production is simulated by injecting water at a constant discharge (1.5 dm^3/h), beneath the silicon layer.

~~This experiment was repeated 12 times with identical input parameters. A six-stage ice stream lifecycle linking outburst flooding, transitory ice streaming and tunnel valley development has been observed for all these simulations (Fig. 2a-f, Fig. 4).~~

Stage 1 (Fig. 2a-3a). A water pocket grows below the centre of the silicon layer and raises its surface by 2 mm. Above the water pocket, the silicon accelerates ($V_{surface} \geq 35\cdot10^{-3}$ mm/~~·~~s~~$^{-1}$~~), and is decoupled from the substratum ($\frac{V_{base}}{V_{surface}} = 75$ to 80%). Below the rest of the silicon layer, lower velocities ($V_{surface} = 8\cdot10^{-3}$ mm/~~·~~s~~$^{-1}$~~, $\frac{V_{base}}{V_{surface}} = 40$ to 50%) indicate higher basal friction. These results are consistent with inferences that meltwater ponding can form pressurised subglacial water pockets associated with basal decoupling, surface uplift, and ice flow acceleration in natural ice sheets (e.g. *Hanson et al., 1998; Elsworth and Suckale, 2016; Livingstone et al., 2016*). In the experiment however, these effects are restricted to an approximately circular region and are not sufficient to produce channelised ice streaming.

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Stage 2 (Fig. 2b-3b). The water pocket expands and migrates towards the margin of the silicon layer. The lack of channels incised in the substratum indicates that this displacement occurs as distributed water drainage not accomplishing erosion. In the silicon layer, the region of surface uplift, basal decoupling and acceleration ($V_{surface} = 18\cdot10^{-3}$ mm/~~·~~s~~$^{-1}$~~, $\frac{V_{base}}{V_{surface}} = 75$ to 85%) expands and migrates downstream with the water pocket. Similar migrations of pressurised subglacial water pockets have been observed or inferred under modern and ancient ice sheets (*Fricker et al., 2007; Carter et al., 2017*), sometimes associated with migrations of regions of ice surface uplift and ice flow acceleration (*Bell et al., 2007; Stearns et al., 2008; Siegfried et* *al., 2016*). The experiment suggests that these water pockets can migrate by distributed drainage and can contribute to the emergence of ice streams.

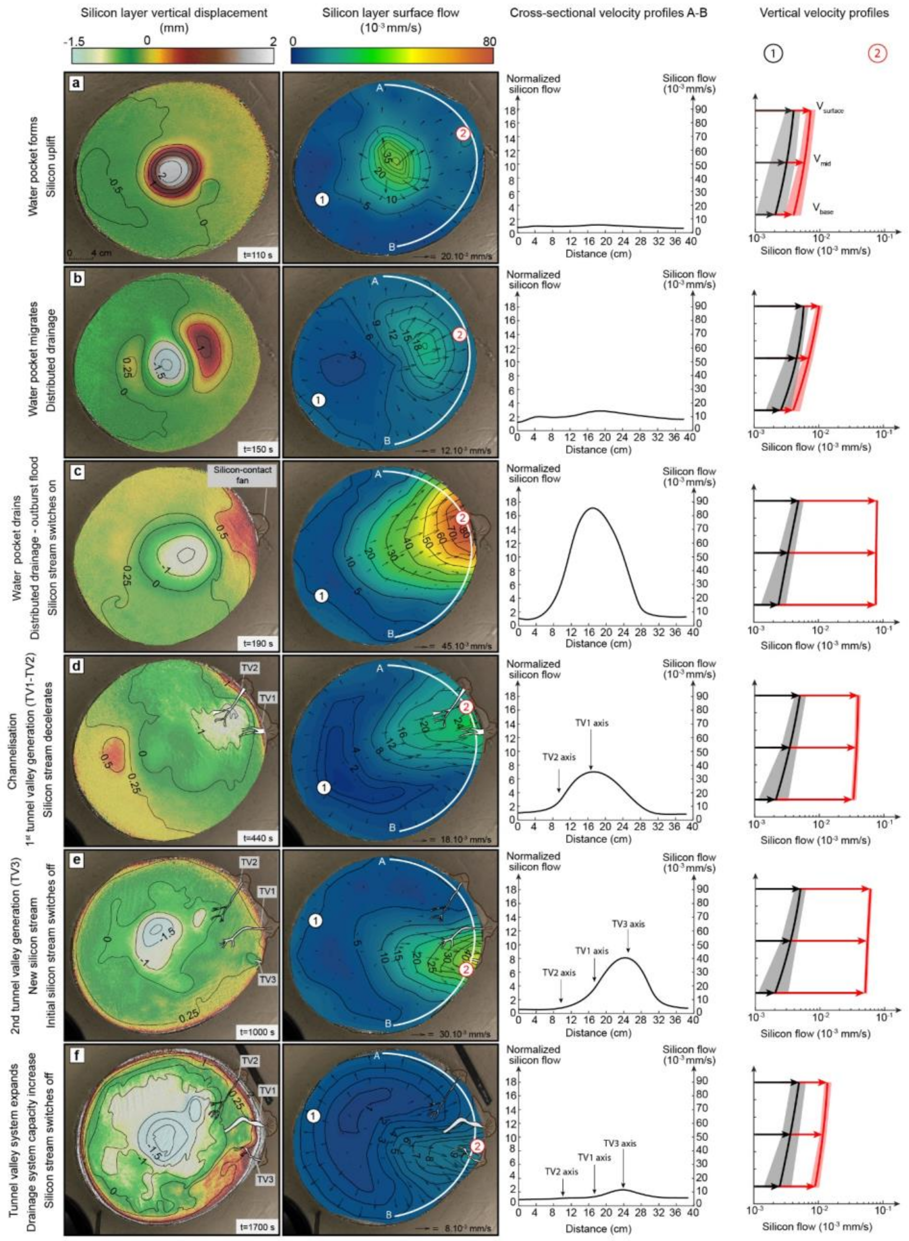

Figure 3. Temporal evolution of the experiment. a, Formation of water pocket, uplift of silicon surface uplift and acceleration. b, Migration of water pocket and overlying region of uplift and accelerated flow. c, Marginal drainage of water pocket and onset of silicon streaming. d, Tunnel valley development and silicon stream deceleration. e, Formation, migration and marginal drainage of a new water pocket, development of a second silicon stream and of a new tunnel valley. f, Decay of the second silicon stream. From left to right: (i) maps of vertical displacements of silicon layer surface, (ii) maps of horizontal velocity at silicon cap surface, (iii) cross-sectional velocity profiles (absolute velocity on right axis, velocity normalised by background velocity on left axis, profile locations indicated by white lines A-B on maps), (iv) vertical velocity profiles for silicon stream (red profiles, locations labelled 1 on maps) and for region opposed to silicon stream (black profiles, locations labelled 2 on maps).

Stage 3 (Fig. 2c-3c). When the water pocket reaches the margin of the silicon layer, it drains suddenly. This marginal outburst flood is still fed by distributed drainage and conveys sand particles eroded from the substratum towards a low-angle marginal sedimentary fan ~~(~~(up to 40 mm long, 30 mm wide and 0.3 mm thick; Fig. S3)~~Fig. S3)~~. Simultaneously, the silicon flow focuses in a stream (200 m~~e~~m wide at the margin) that propagates upstream from the silicon margin to the water injection area. This stream immediately peaks in velocity ($V_{surface} = 80 \cdot 10^{-3}$ mm/~~·~~s~~$^{-1}$~~, 16 times higher than the surrounding silicon) and is entirely decoupled from its substratum ($\frac{V_{base}}{V_{surface}} > 90\%$). Although similar relations between outburst floods and ice flow accelerations have been suspected in modern (*Alley et al., 2006; Bell et al., 2007; Stearns et al., 2008*) and past (*Livingstone et al., 2016*) ice sheets, they have been documented for valley glaciers only (~~*Kamb, 1985*~~*e.g. Anderson et al., 2005*): there, they can produce sudden meltwater discharges that exceed the capacity of distributed subglacial meltwater drainages and promote basal decoupling and ice flow acceleration (e.g. *Magnússon et al., 2007*). The experiment confirms that outburst floods can promote basal decoupling and trigger ice streaming in ice sheets (*Fowler and Johnson, 1995*).

Stage 4 (Fig. 2d-3d). The distributed subglacial drainage system starts to channelise: two valleys (TV1 and TV2) appear below the margin of the silicon layer and gradually expand by regressive erosion of the substratum. At this stage, TV1 is 30 mm long, 12 mm wide and 0.5 mm deep; TV2 is 80 mm long, 10 mm wide and 0.5 mm deep. These valleys, with their constant widths, undulating long profiles and radial distribution, are analogue to natural tunnel valleys in their dimensions, shapes and spatial organization (*Lelandais et al., 2016*; Fig. ~~S~~4). They are fed by distributed water drainage. The sand eroded from the substratum transits through these valleys and accumulates in high-angle marginal sedimentary fans, higher in elevation than the valley floors (TV1 fan is up to 27 mm long, 30 mm wide and 0.5 mm thick; TV2 fan is up to 20 mm long, 24 mm wide and 1 mm; Fig. S3~~Figs. 4 and S3-4~~). In response to progressive channelisation of the water drainage into the expanding valleys, the silicon stream narrows and slows down (120 m~~e~~m wide at the margin; $V_{surface} = 24 \cdot 10^{-3}$ mm/~~·~~s~~$^{-1}$~~). The silicon stream, still channelised, is still flowing 8 times faster than the rest of the silicon layer and is still decoupled from the substratum ($\frac{V_{base}}{V_{surface}} > 85\%$). These results are consistent with inferences that channelisation of hitherto distributed subglacial water drainage systems can occur and reduce ice flow velocity after outburst floods (*Magnússon et al., 2007; Kamb, 1987; Retzlaff and Bentley, 1993*), and can be responsible for narrowing and deceleration of ice streams (*Raymond,*

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1987; Retzlaff and Bentley, 1993; Catania et al., 2006; Beem et al., 2014; Kim et al., 2016). At this stage of the experiment, this transition, which corresponds to the initiation of tunnel valleys, is not sufficient to stop ice streaming however.

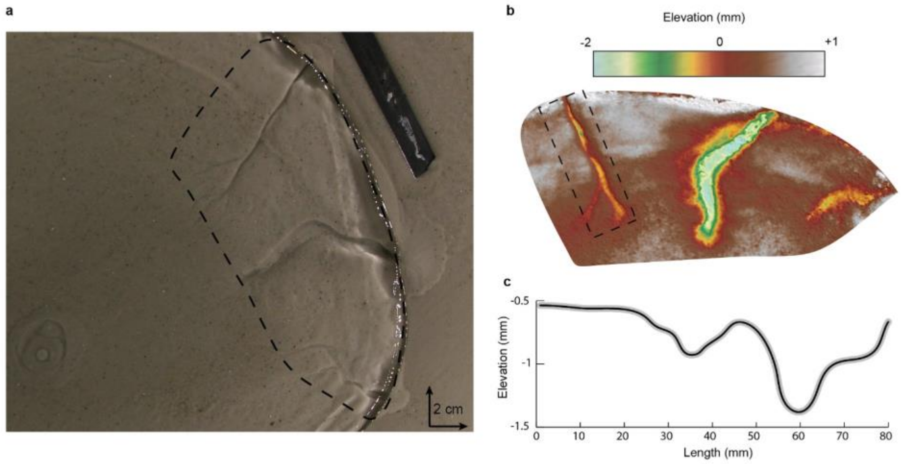

Figure 4. Digital Elevation Model (DEM) of an experimental tunnel valley and its associated longitudinal profile. a, Snapshot of the tunnel valley system. b, DEM of the tunnel valley corresponding to the one highlighted by a dashed box in a. c, Undulating longitudinal profile of the tunnel valley bottom extracted DEM shown in b

Stage 5 (Fig. 2e-3e). A new transient water pocket grows below the silicon layer, migrates and drains as an outburst flood, thus forming a new low-angle marginal sedimentary fan with at lateral offset of 4 cm with respect to TV1. This induces the activation of a second stream ($V_{surface}$ = $40 \cdot 10^{-3}$ mm/~~·~~s~~$^{-1}$~~) decoupled from its substratum ($\frac{V_{base}}{V_{surface}} = 80\%$) and the initiation of a new radial valley (TV3), in a hitherto slow-moving region of the silicon cap. Simultaneously, the first silicon stream switches off ($V_{surface}$ = $10 \cdot 10^{-3}$ mm/~~·~~s~~$^{-1}$~~), recouples to its substratum ($\frac{V_{base}}{V_{surface}} = 30\%$), but water and sand still flow through TV1 and TV2. At this stage, TV1 is 100 mm long, 8 mm wide and 0.7 mm deep and its fan is up to 21 mm long, 40 mm wide and 1.1 mm thick; TV2 is 80 mm long, 0.75 mm deep and 0.6 mm deep and its fan is up to 20 mm long, 28 mm wide and 1.6 mm thick. This result is consistent with inferences that natural ice streams can switch on/off, surge or jump in location in response to changes in subglacial water drainage reorganization (*Beem et al., 2014; Hulbe et al., 2016; Catania et al., 2012; Le Brocq et al., 2013*). The experiment further suggests that this complex behaviour is controlled by the growth and migration, in various possible directions, of transient pressurised subglacial water pockets that form successively as long as the discharge capacity of tunnel valleys systems is not sufficient to drain efficiently the available meltwater.

Stage 6 (Fig. 2f-3f). Since their initiation, TV1, TV2 and TV3 have progressively increased in width, depth and length. At this stage TV1 is 100 mm long, 17 mm wide and 1.2 mm deep and its fan is 28 mm long, 4 mm wide and 1.5 mm high at the maximum; TV2 is 80 mm long, 10 mm wide and 0.8 mm deep and its fan is up to 16 mm long, 23 mm wide and 1.6 mm thick ; TV3 is 60 mm long, 11 mm wide and 0.55 mm deep and its fan is up to 14 mm long, 23 mm wide and 0.7 mm thick. Their overall volume and discharge capacity have thus increased (Fig. 5~~3~~). In response to this increased drainage efficiency, the second stream gradually decays ($V_{surface}$ = 5·10^3 mm/~~.~~s~~$^{-1}$~~), recouples to its substratum ($\frac{V_{base}}{V_{surface}} = 35\%$), and the silicon layer ultimately recovers a radial flow pattern (Fig. 3~~2~~f). This result is consistent with the inference that ice streams may decelerate and even switch off in response to reduction of subglacial water pressures when efficient subglacial water drainage systems develop (*Retzlaff and Bentley, 1993; Beem et al., 2014; Livingstone et al., 2016; Kim et al., 2016*). In the experiment, this development is governed by the expansion of tunnel valley networks. Large glaciotectonic thrust masses at the ice margin near tunnel valleys fans are generally assumed to be field evidences of a fast ice flow stage prior to drainage through tunnel valleys (*Hooke and Jennings, 2006*).

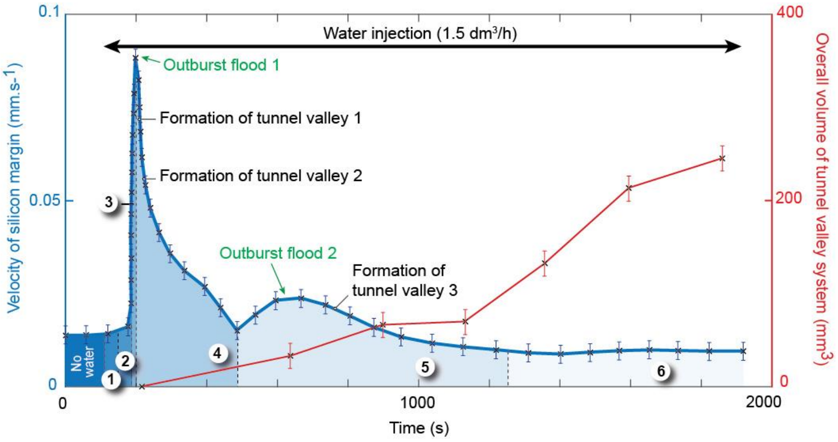

Figure 5~~3~~. Progressive expansion of overall volume of tunnel valleys system vs. velocity of silicon margin through the experiment. The circled numbers correspond to the six-stages of the proposed ice stream lifecycle.

3.2. Experimental reproducibility and variability

~~4. Proposed lifecycle of transitory ice streams~~

This experiment has been reproduced 12 times with identical input parameters. We always observe the same processes and events acting in a similar chronological order : (1) water pocket forms; (2) water pocket migrates; (3) water pocket drains (outburst flood) and silicon stream switches on; (4) Tunnel valleys form in response to channelisation ; silicon stream slows down (5) and finally switches off (6) in response to the increase of drainage efficiency during tunnel valley development . However, despite this consistency in the progress of all simulations we ran, some variability has been detected. We measured different migration rates for the water pocket ranging from 30 s to 80 s that may result from small changes in subglacial topography

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Mis en forme : Normal, Retrait : Première ligne : 0,63 cm, Sans numérotation ni puces and in the dynamics of silicon-bed decoupling. Considering a constant water discharge and the characteristics of the experiment, a longer period of migration implies: a longer period of water storage and a bigger water volume released at the silicon margin during the pocket drainage .We therefore recorded peak velocities for water pocket drainage ranging from 6.10^{-3} to 12.10^{-3} $mm.s^{-1}$. In response to variations of the water volume drained at the margin and the peak discharge, the maximum width of the silicon stream varies from 120 to 250 mm. The magnitude of the outburst flood triggered during water pocket drainage also influences the amount of tunnel valleys that will later forms during the channelisation stage. A high magnitude outburst flood generates a wider erosion beneath the silicon that will be suitable for the development of multiple tunnel valleys. Hence, the amount of tunnel valleys at the end of the experiments ranges from 1 to 5 with 1 to 3 tunnel valleys formed simultaneously during the initiation of the channelisation stage. These valleys range from 40 to 120 mm long, 3 to 18 mm wide and 0.3 to 1.8 mm deep. During tunnel valleys development, the evolution of drainage efficiency varies between the experiments. A relatively inefficient system of tunnel valley induces upstream water pocket formation. As observed in Figure 3e, the drainage of this belated water pocket may provoke water re-routing behind the silicon and subsequent lateral migration of the silicon stream. We counted 0 to 2 events of silicon stream migration for single experiments. Finally, the time required to reach the phase of ice stream decay highly depends on the amount of tunnel valleys formed during the experiments and their progressive development. We observed a lifetime for the silicon stream ranging from 500 s to 1700 s, correlated with the evolution of the drainage efficiency during tunnel valleys development.

4. Proposed lifecycle of transitory ice streams

The experiment demonstrates that, on flat and homogenous beds, ice streams may arise, progress and decay in response to mechanical interactions between ice flow, subglacial water drainage and bed erosion. On uneven or heterogeneous beds (not simulated in this model), these interactions may additionally be enhanced or disturbed by spatial variations in the subglacial topography, geology and geothermal heat flux (e.g. *Bentley, 1987; Blankenship et al., 1993; Anandakrishnan et al., 1998; Bourgeois et al., 2000; Winsborrow et al., 2010*). The complex rheology of glacial ice and subglacial till (both generally soften with increasing strain rate, temperature, water content and anisotropy) may also enhance these interactions by increasing velocity contrasts between ice streams and their slower-moving margins. This may lead to the development of narrower ice streams with higher velocities and sharper lateral shear margins in natural ice sheets than in the experiment (*Raymond, 1987; Perol et al., 2015*).

Although the complexity of glacial systems cannot be fully modelled using the present experimental setup, our results highlight the critical connection between ice streams and tunnel valleys. As reviewed in *Kehew et al. (2012)* and suggested in *Ravier et al. (2015)* this relation was suspected from the occurrence of tunnel valleys on ancient ice streams beds. However, it raised a contradiction: subglacial meltwater pressures are generally supposed to be high below ice streams (*Bennett, 2003*) while tunnel valleys are generally assumed to operate at lower water pressures (*Marczinek and Piotrowski, 2006*). Although speculated from field evidences, our results demonstrate that ice streaming, tunnel valley formation, release of marginal outburst floods and subglacial water drainage reorganization may be interdependent parts of a single ice stream lifecyle that involves temporal changes in subglacial meltwater pressures (Fig. 6).

1. Ice stream seeding**.** A prerequisite to the activation of ice streams is the formation of pressurised subglacial pockets by meltwater ponding in ice sheet hinterlands. Approximately circular regions of surface uplift and accelerated ice flow develop above these transient water pockets.

2. Ice stream gestation. Pressurised water pockets migrate downstream by distributed water flow. Regions of surface uplift and accelerated ice flow migrate accordingly.

3. Ice stream birth**.** Once water pockets reach ice sheet margins, they drain as outburst floods. At that time, ice streams switch on, peak in velocity and propagate towards ice sheet hinterlands as decoupled corridors of accelerated ice flow underlain by pressurised distributed water drainage.

4. Ice stream aging. Subglacial water drainage then channelises gradually: tunnel valleys fed by pressurised distributed drainage start to form at ice stream fronts. Subsequent expansion of tunnel valleys by regressive erosion progressively increases their overall discharge capacity, lowers subglacial water pressures and provokes gradual ice stream recoupling and deceleration. The response of ice stream dynamics to drainage channelisation and tunnel valley development might be underestimated due to the high erodability of the subglacial bed used in the experiment.

5. Ice stream rebirth (relocation or surge). As long as tunnel valley systems keep low drainage capacities, successive pressurised subglacial water pockets can form, migrate and drain as marginal outburst floods. On even and homogeneous ice sheet beds, the subglacial water drainage is controlled by the surface topography of ice sheets: subtle temporal changes in this topography may thus be able to produce consecutive generations of ice streams and tunnel valleys at different locations and with different flow directions. These jumps in locations and directions may be responsible for the formation of independent, but sometimes intersecting, ice streams corridors and tunnel valleys networks on some ancient ice sheet beds (*Jørgensen and Piotrowski, 2003; Fowler and Johnson, 1995*). By contrast, if subglacial water routes and ice flow are constrained by bed heterogeneities, migration of successive subglacial water pockets along predetermined paths may induce sequential ice stream surges (*Fowler and Johnson, 1995; Hulbe et al., 2016*) and participate in the gradual development of complex tunnel valley systems at fixed places, like the Dry Valleys “Labyrinth” in Antarctica (*Lewis et al., 2006*).

6. Ice stream senescence. Ice streams may ultimately switch off when drainage capacities of tunnel valley systems are sufficient to limit subglacial water overpressures. The progressive decay of an ice stream activity can be partially produced by the thinning of the ice layer and the subsequent reduction of the stress driving ice flow in ice stream corridors (*Robel et al., 2013*). Our experiments display negligible thinning prior to ice stream decay. A constant water discharge being applied in experiments, we demonstrate that increased drainage efficiency during tunnel valley development can solely be responsible for ice stream slowdown. Tunnel valleys and ice streams are frequently found to co-exist and with the many examples reported from the southern margin of the Laurentide Ice Sheet (*Patterson, 1997; Livingstone and Clark,*

2016). In one case, development of tunnel valleys has been suggested to have led to stagnation of ice flow at an ice stream terminus (*Patterson, 1997*), a process that we have now demonstrated by modelling. This further suggests that tunnel valleys development could secure ice sheet stability as hinted by *Marczinek and Piotrowski. (2006)* by preventing ice stream destabilisation. We apply a constant meltwater discharge to our model, however meltwater production and discharge in a subglacial system fluctuates at different times scales (day, year, decades). Fluctuating water production may have further implication on the size of ice streams, the size and amount of tunnel valleys that develop through time or the timescale involved in ice sheet destabilization and stabilization. The oscillation in water production could strengthen and multiply the life cycles of some transitory ice streams, already deciphered with a constant water discharge in this study.

In a global change context, phenomena of ice stream stabilisation would requires that pre-existing and newly forming tunnel valleys systems expand sufficiently fast to accommodate increased meltwater production. Investigating the processes and rates of tunnel valley development are more than ever warranted to better assess ancient and present-day ice sheets behaviour.

~~The experiment demonstrates that, on flat and homogenous beds, ice streams may arise, progress and decay in response to mechanical interactions between ice flow, subglacial water drainage and bed erosion. On uneven or heterogeneous beds, these interactions may additionally be enhanced or disturbed by spatial variations in the subglacial topography, geology and geothermal heat flux (*Bourgeois et al., 2000; Winsborrow, 2010*). The complex rheology of glacial ice and subglacial till (both generally soften with increasing strain rate, temperature, water content and anisotropy) may also enhance these interactions by increasing velocity contrasts between ice streams and their slower-moving margins (see methods for further details). This may lead to the development of narrower ice streams with higher velocities and sharper lateral shear margins in natural ice sheets than in the experiment (*Raymond, 1987; Perol et al., 2015*).~~

~~Although the complexity of glacial systems cannot be fully modelled using the present experimental setup, our results highlight the critical connection between ice streams and tunnel valleys. This relation was suspected from the occurrence of tunnel valleys on palaeo ice stream beds (*Kehew et al., 2012; Ravier et al., 2015*), but raised a contradiction: subglacial meltwater pressures are classically believed to be high below ice streams (*Bennett, 2003*), while they are suspected to be low in tunnel valleys (*Marczinek and Piotrowski, 2006*). Our results provide a solution to this apparent contradiction: they demonstrate that ice streaming, tunnel valley formation, release of marginal outburst floods and subglacial water drainage reorganization may be interdependent parts of a single lifecycle that involves temporal changes in subglacial meltwater pressures (Fig. 4).~~

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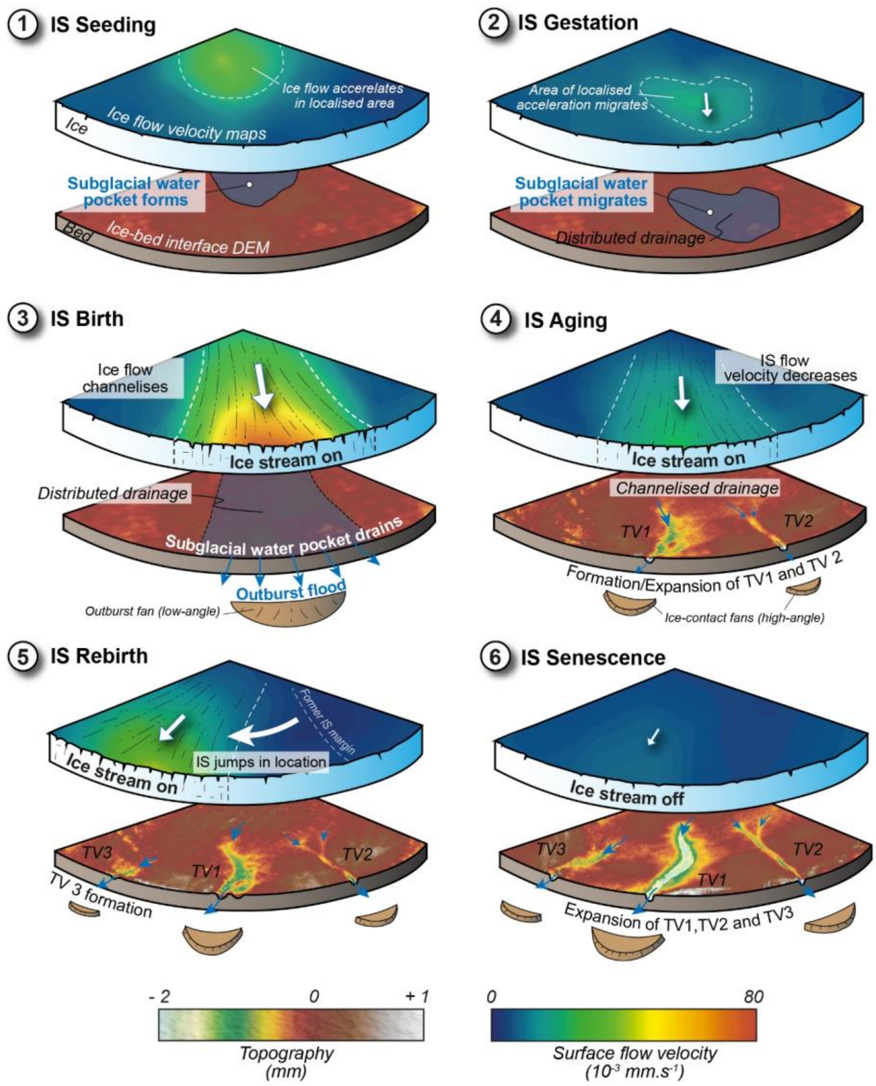

Figure 64. Chronological sequence with interpretative sketches illustrating the proposed ice stream lifecycle and the relations with tunnel valley development. Basal topography and surface flow velocity maps are derived from the experiment.

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~~5. Conclusion~~

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5. Conclusion

The transitory and mobile nature of ice streams may be understood in the framework of a model lifecycle that involves temporal changes in subglacial meltwater pressures and arises from interactions between ice flow, subglacial water drainage and bed erosion. In this model lifecycle transitory ice streams arise, progress and decay in response to subglacial flooding, changes in type and efficiency of subglacial drainage, and development of tunnel valleys. These results are consistent with (and reconcile) a variety of otherwise detached observations performed at different timescales and at different places, on modern and ancient natural ice streams. One of the most novel outcomes of this study, is that subglacial tunnel valley development may be crucial in controlling ice stream vanishing and perhaps, as a consequence, in preventing catastrophic ice sheet collapses during periods of climate change. The processes and rates of tunnel valley development are thus major issues for predicting the forthcoming behaviour of present-day ice sheets and for assessing their contribution to the release of ice and freshwater to the ocean. The innovative experimental approach, used here opens new perspectives on the understanding of subglacial processes controlling ice sheet dynamics and destabilisation.

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Author contributions:

OB, RM, ER and SP conceived this research and gathered funding. TL designed and conducted the experiments (setup, monitoring and post-treatment), with contributions by RM and PS. TL, ER, OB, CDC, SP and RM contributed to the interpretation of the results and of their natural implications. TL wrote the first draft of the manuscript; ER, OB, SP and CDC contributed substantially to its present version.

Competing interests:

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The authors declare that they have no conflict of interest

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