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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 model ice streams switch on when subglacial water pockets drain as marginal outburst floods. Then they decelerate as basal coupling increases as a consequence of the lubricating water drainage system spontaneously organising itself into channels that erode tunnel valleys. They 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 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, 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 them of them as primary drivers or 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.

Connections between ice stream activity and subglacial hydrology are supported by the occurrence of geomorphic markers of meltwater drainage on palaeo-ice stream beds (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. Tunnel valleys are elongated and over-deepened hollows, up to hundreds of kilometres long, several kilometres wide and hundreds of meters deep. Their formation is generally attributed to subglacial meltwater erosion but there is still no consensus on their development processes and on their relationship to ice streaming. 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).

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.

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). 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 reconciles into a single story several detached inferences, derived from observations at different timescales and at different places on modern and ancient ice streams.

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) (Hindmarsh, 2009). Considering all these processes and components simultaneously is thus a challenge for modelling, especially with numerical computational means (Fowler and Johnson, 1995; Marshall, 2005; Bingham et al., 2010). 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). 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 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).

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 = 5·10^{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. 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

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

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).

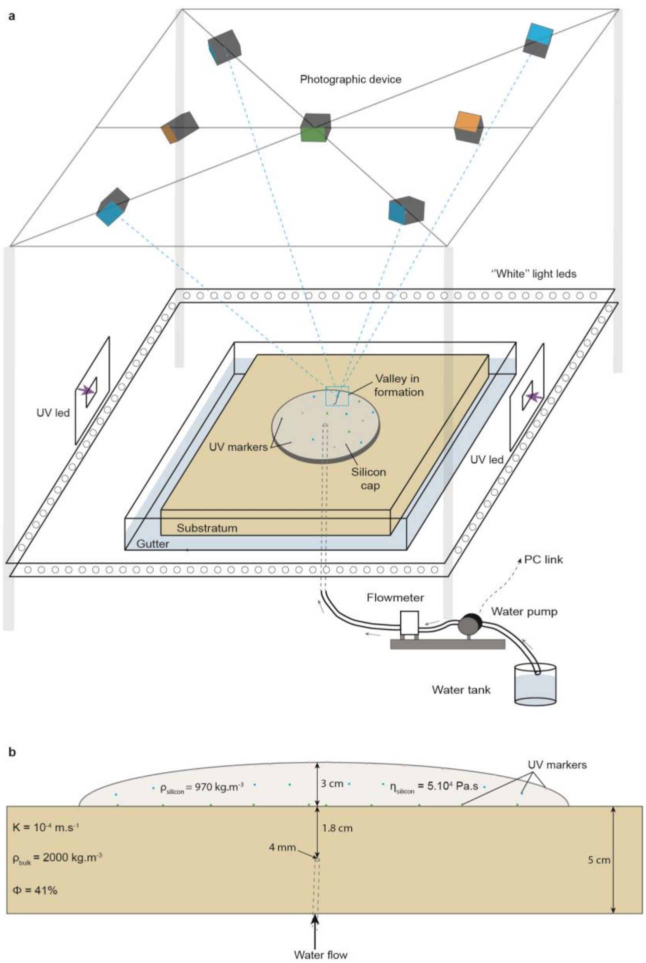

Figure 1. Description of the analog device used in this study. a, Overview of the analog device. The analog device consists in a 70 cm long, 70 cm wide and 5 cm deep glass box filled with saturated and compacted sand simulating the substratum. The ice sheet portion is simulated by a circular layer of 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 analog device displaying the position of the UV markers and the physical characteristics of both the substratum and the silicon layer.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

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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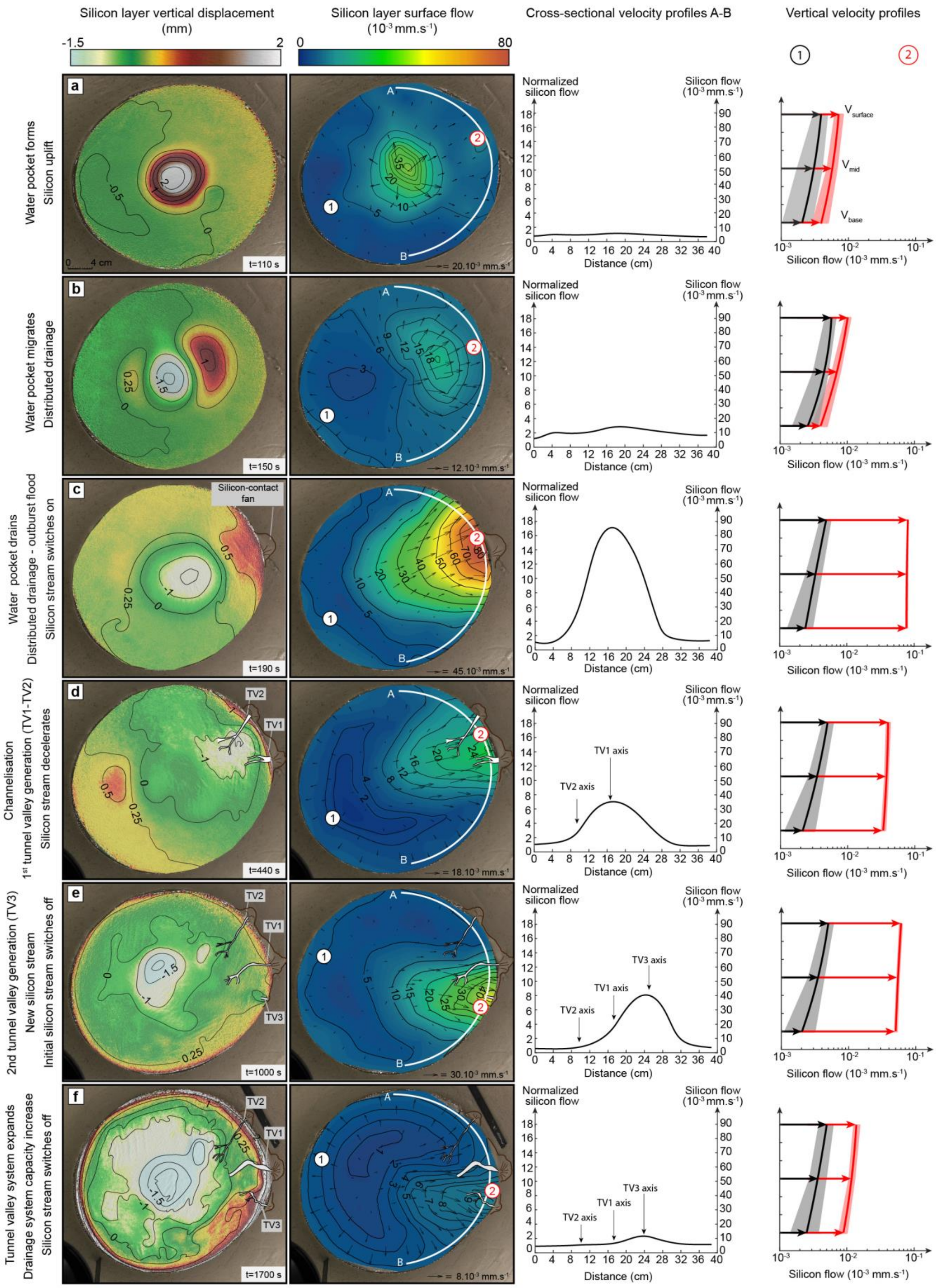

168

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

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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

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 ($V_{surface} < 3 \cdot 10^{-3}$ mm·s^{-1}) to the margin ($V_{surface} = 8 \cdot 10^{-3}$ 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). 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 ($V_{surface} \geq 35 \cdot 10^{-3}$ 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 ($V_{surface} = 8 \cdot 10^{-3}$ 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 (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.

Stage 2 (Fig. 2b). 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 ($V_{surface} = 18 \cdot 10^{-3}$ 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

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

al., 2016). The experiment suggests that these water pockets can migrate by distributed drainage and can contribute to the emergence of ice streams.

Stage 3 (Fig. 2c). 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 (Fig. S3). Simultaneously, the silicon flow focuses in a stream (20 cm 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): there, they can produce sudden meltwater discharges that exceed the capacity of distributed subglacial meltwater drainages and promote basal decoupling and ice flow acceleration (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). 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. 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. S4). 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 (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 (12 cm 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, 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.

Stage 5 (Fig. 2e). 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. This result is consistent with

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

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). Since their initiation, TV1, TV2 and TV3 have progressively increased in width, depth and length. Their overall volume and discharge capacity have thus increased (Fig. 3). In response to this increased drainage efficiency, the second stream gradually decays ($V_{surface} = 5 \cdot 10^3$ mm.s^{-1}), recouples to its substratum ($\frac{V_{base}}{V_{surface}} = 35\%$), and the silicon layer ultimately recovers a radial flow pattern (Fig. 2f). 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.

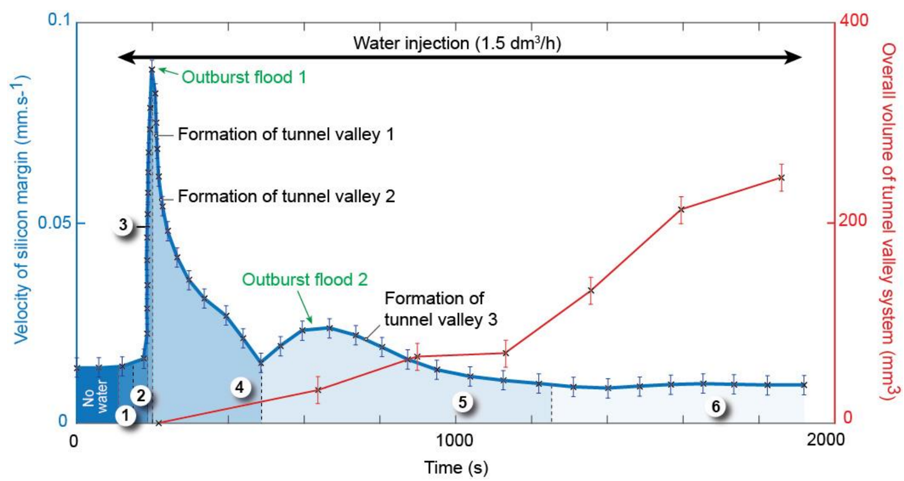

Figure 3. Progressive expansion of overall volume of tunnel valleys system vs. velocity of silicon margin through the experiment. The circled numbers correspond to the six-stages of the proposed ice stream lifecycle.

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, 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,

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

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).

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.

5. Ice stream rebirth (relocation or surge). As long as tunnel valley systems keep low drainage capacities, successive pressurized subglacial water pockets can form, migrate and drain as marginal outburst floods. On even and homogeneous ice sheet beds, 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 palaeo 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;

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
Manuscript under review for journal The Cryosphere
Discussion started: 8 May 2018

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. 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 validates the hypothesis that tunnel valley development can secure ice sheet stability by preventing catastrophic ice stream collapses (Marczinek and Piotrowski, 2006), which could represent early stages of unstoppable ice sheet disintegrations (Hulbe, 2017) In a global change context, this possible stabilisation however requires that pre-existing and/or newly forming tunnel valley systems expand sufficiently fast to accommodate increased meltwater production. 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, which alters global sea level and oceanic circulations.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-71
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Discussion started: 8 May 2018

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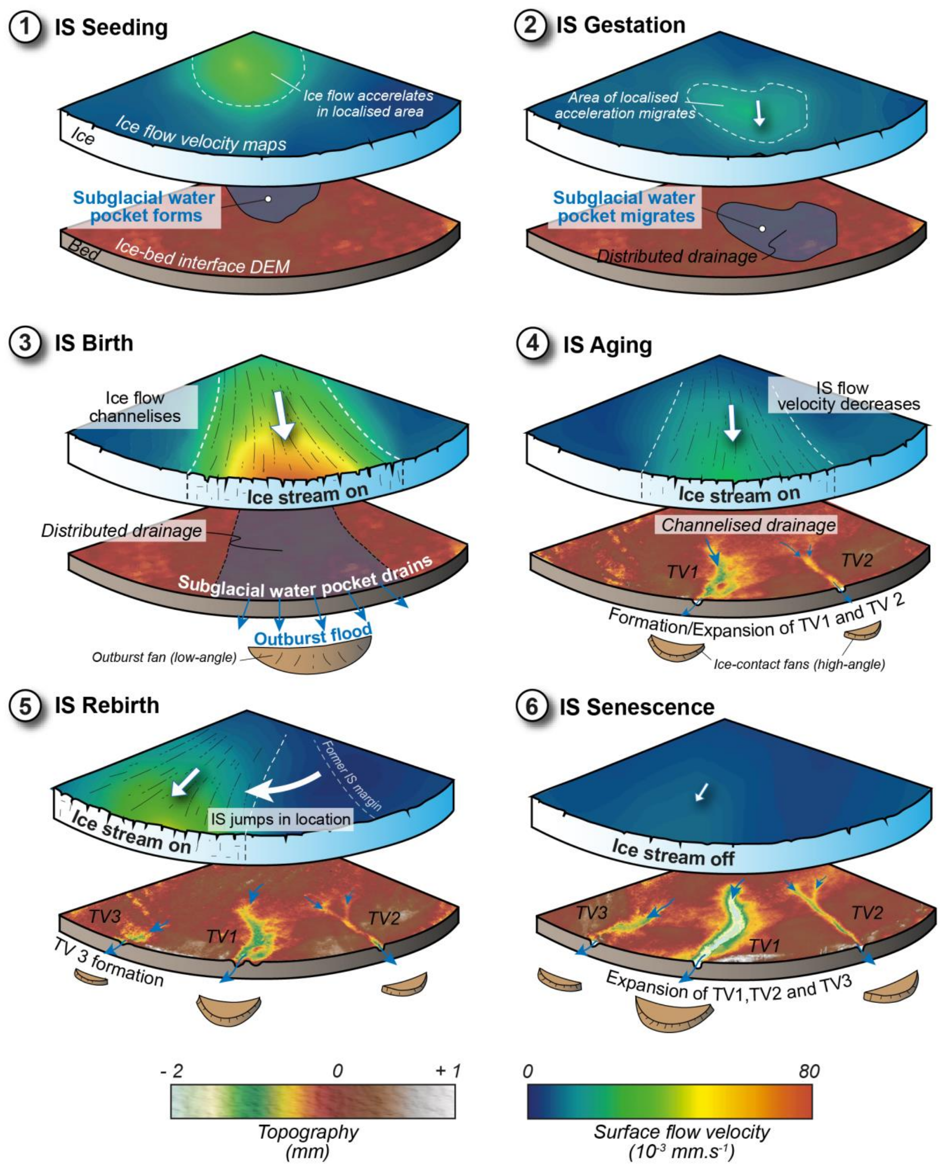

Figure 4. Chronological sequence with interpretative sketches illustrating the proposed ice stream lifecycle and the relations with tunnel valley development. Basal topography and surface flow velocity maps are derived from the experiment.

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 behavior 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

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:

The authors declare that they have no conflict of interest

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