

Icings: their structure and influence on the hydrological network of a small arctic glacier forefield

É. Bernard¹, J.-M. Friedt^{2†}, E. Kuschel³, A. Prokop^{4,5}, F. Tolle¹, M. Griselin¹

¹ ThéMA, UMR CNRS 6049, 32 rue Mégevand, 25000 Besançon, France

² FEMTO-ST, Time & Frequency, UMR 6174, 15 avenue des Montboucons, 25000 Besançon, France

³ Department of Civil Engineering and Natural Hazards, Institute of Applied Geology, University of Natural Resources and Life Sciences, Vienna, Austria

⁴ Department of Geology, University of Vienna, Josef-Holaubek-Platz 2, /UZAI, 1090, Vienna, Austria

⁵ Snow Scan GmbH, Stadlauer Strasse 31, 1220 Vienna, Austria

† Corresponding author: jmfriedt@femto-st.fr

Abstract

We address the evolution of a proglacial hydrographic network under the influence of icings over a small Arctic glacier forefield in the context of glacier retreat. The newly deglaciated area allows glacial rivers to carve new channels as fine-grained sediment is exposed. The main glacier outlet flow from one channel to another is controlled by icings over the years. The research methodology involves analyzing optical camera images for qualitative observations of morphological evolutions, and LiDAR data for quantitative estimates of the icings' volume as well as riverbed profiles. Ground Penetrating Radar (GPR) is used to investigate the internal structure of icings and its possible influence on runoff streams. Based on the seasonal persistence of icings and their spatial extent, we observe that icings act as dams channelling the main glacier outlet between canyons carved in the deglaciated areas and, when lasting long enough, even define long-term outflow paths. The internal structure of icings suggest that upstream, deep icings are permeable to water flow while downstream dense, shallow icings act as watertight obstacles, contributing to their dam effect.

1 Introduction

Arctic proglacial moraines, which are areas of land exposed by retreating glaciers, have been undergoing significant morphological changes in recent years. These physical transformations are primarily driven by increased runoff [1, 2, 3] resulting from glacial retreat and increased rainfall. This influx of freshwater has a major impact on the reshaping of the newly exposed sediments [4, 5]. One example of these changes is the occurrence of short warm events with heavy rainfall and flash floods, caused by melting and rain, which are becoming more common in the Arctic ([6, 7]). These events trigger new hydrological behaviors

that significantly alter the shape of the forefield areas [8, 9]. Unstabilized terrain areas are particularly affected by hydrological activity, resulting in rapid changes in landforms [10].

Additionally, the phenomenon of icings [11], also known as aufeis [12], typical in the Arctic, still occurs in forefields of Svalbard glaciers despite glacial retreat ([13, 14]). Among features that clearly control forefield hydrography, it appears that icings are part of cryospheric features impacting notably the source-to-sink dynamics ([15, 16]). While they usually persist until the end of summer with a variable decrease in size, they have been melting and completely disappearing over the past decade, releasing the proglacial river beds entirely ([17]). As a consequence, the hydrological regime of proglacial rivers is impacted. ([18, 19, 20]), described icings as masses of frozen water, developed as layered column ice as a result of consolidation of successive underground or surface water flows in the cold season of the year. From above, it results in more or less large frozen water patches on glacier forefields. Through their composition and formation, icings function as a reservoir that stores water in the form of compacted ice or ice needles. These icings are highly sensitive to climatic conditions, driving their emergence and disappearance, and have a significant impact on the shape of the region’s hydrological network [21, 13]. Description and physical processes of these rather unique physical formations were analyzed by [21] and updated by [22, 23] which summarize the main characteristics ([24, 25]). Researchers have found that icings located further upstream have a greater influence on the hydrological behavior of the area. In some cases, icings can redirect the flow of runoff when they are located at the interface between glacial and periglacial areas [16, 26]. The Austre Lovénbreen Arctic glacier outflow river serves as an example of this redirection [27], as it was rerouted due to a plug created by icings and an accumulation of sediments. Strong runoff, floods, rain-on-snow (ROS) events, and rapid melting result in the transport of large amounts of sediment over the moraine and outwash plain ([28, 29]), and yet causing minimal geomorphological changes ([30, 31, 19]).

These observations raise questions about the potential of icings to largely impact the entire hydrographic system, similar to the impact of moraine-dammed lakes. The potential failure of icings or at least their structural transformation, from watertight to porous, may affect the global geomorphology of outwash plains.

This study aims to investigate how icings can (re)shape the geometry of hydrographic networks. Based on a fine spatial-temporal approach, we thus 1) analyze the morphological changes over the proglacial area since 2012 in order to 2) assess the role played by icings and to study the way in which they can influence flows and therefore modify the degree of erosion. This point will be highlighted by 3) investigating the internal structure of icings to document how it forces the hydrological processes.

The research methodology involves analyzing optical camera images and LiDAR data to observe and quantify icings themselves as well as morphological changes in the hydrographic network and the

moraine area. Ground Penetrating Radar (GPR) is used to investigate the internal structure of icings and its influence on the water circulation. The resultant interpretation of the internal structure of the icings elucidate a mechanism for the formation of proglacial hydrographic networks, which subsequently influences the channel flow dynamics within the moraine.

2 The geographical setting

The geographical settings for this study is the Brøgger peninsula, located on the west coast of Spitsbergen, which is home to small alpine-type glaciers (Fig. 1).

Austre Lovénbreen (AL) is a small land-terminating glacier filling a north-facing catchment within a 10.5 km² basin. It has exhibited a continuous retreat, started at the end of the LIA (Little Ice Age) ([32]). Since the 90s, an accelerating rate of melting was measured([28]) with an annual retreat rate of the front of $-19.2 \pm 0.3 \text{ m}\cdot\text{a}^{-1}$. This led to a constant increase in a strip of loose, easy-to-move, sediment area in contact with the glacier front. In contrast, in such a context of glacier retreat, the moraine has experienced an area increase of about 45% between the maximum glacier front extent and today ([33, 27]), currently totaling an area of 2 km².

Changes in the precipitation regime, i.e. an increase of rainfall, has led to an increase of runoffs ([34]). In addition, the formation of ice lenses in the snowpack due to winter rainfall results in the rapid release of stored water during the melting season ([35, 36]). Hence, the surface hydrological activity involving both runoffs and outflows have radically changed ([1]): according to [37], this massive contribution of water discharge means that proglacial channel mobility and outlet migration lead to the reworking of glaciogenic sediments throughout the recent period of glacial retreat.

In this work, we focus on the proglacial area of Austre Lovénbreen due to its continuous retreat and the major visible changes in hydrological activity it has experienced.

Currently, Austre Lovénbreen is drained by 2 main streams referred to as eastern and western outlets thereafter (Fig. 1). These 2 streams are unbalanced since the eastern outlet is mostly active as a response to active layer melting, unless the path to the western outlet, is blocked as will be discussed in this article (section 5). Conversely, the western outlet concentrates most of the outflows from both subglacial drainage and surface melting of the glacier.

3 Materials and methods

The research methodology outline starts by investigating visible optical camera images collected automatically for two years in front of the newly carved channel to assess geomorphological reshaping of the

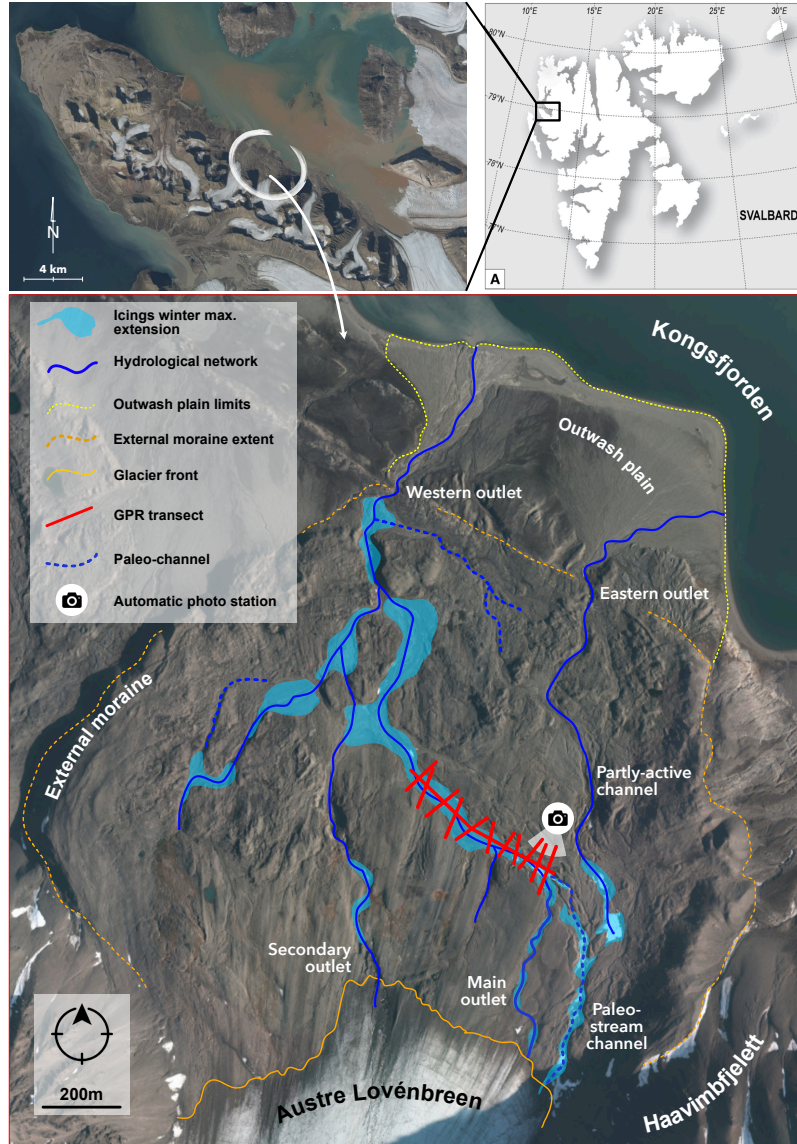


Figure 1: Geographical settings, with increasing magnification counter-clockwise from top-right, and location of the various sensors on the moraine, including the GPR tracks (red lines) and automated cameras (camera symbol with the conic shape indicating the field of view). The LiDAR measurements were collected from the Haavimb summit on the eastern side of the bottom figure.

whole hydrological network, as well as opportunistic aerial views of the glacier basin. Having observed local changes on time-series of oblique-view ground-based cameras with high temporal resolution, the investigation is extended to the whole moraine by analyzing differences of Digital Elevation Model (DEM) derived from LiDAR point clouds. Because icings were highlighted as the source of the outflow path change, their internal structure is investigated using GPR.

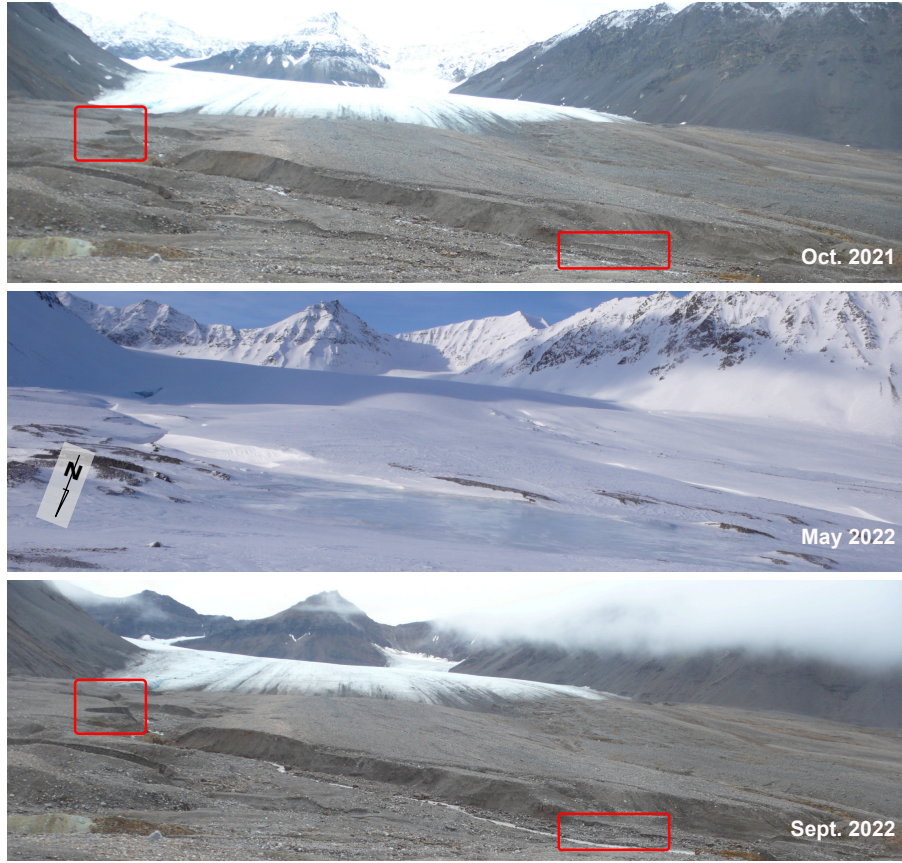


Figure 2: Three images collected by an automated camera facing the icings in October 4th 2021, May 1st 2022 and Sept 8th 2022, all illuminated from the same direction since collected at noon. From one year to another, the banks, unconsolidated and unstable, collapsed in several sections, mainly into the meanders. The red rectangles highlight two of these features evolving from autumn 2021 to autumn 2022.

3.1 Optical digital cameras

In the framework of a long-lasting permanent observatory of AL, a set of automated digital cameras was deployed around the glacier basin since 2007, with the current investigation focusing on the setup observing the moraine area. Each Leica DLux camera is fitted with a dedicated microcontroller board for triggering picture capture every day at 8, 12 and 16 h local time. The images are stored for later manual recovery: all pictures were collected by the camera facing the icings from April 2021 to September 2022, providing a continuous observation dataset. This setup allows for precise observation of the step-by-step formation and subsequent disappearance of downstream icing.

An example of images from the camera facing the icings is provided in Fig. 2, highlighting some areas of significant change (i.e. the collapse of the torrent banks, the digging of meanders) from one season to another with red rectangles. We notice that these regions are all grouped around the newly carved channel where the outlet river is flowing.

In addition to the systematic observation of the icings from a fixed location by the automated camera, field trips in spring and autumn allow for investigating the landscape in which icings are formed. During field trips, manual georeferenced pictures are collected on regions of interest (Fig. 3): these pictures will provide a qualitative context in which to interpret the quantitative measurements from the LiDAR and GPR. These measurement techniques are presented in the next sections.

3.2 LiDAR

Qualitative morphological and topographical changes (i.e. filling of lakes, erosion, hydrographic network modification) were identified thanks to the pictures collected by the automatic cameras and manually during field trips. The main concern is how recent changes in periglacial hydrology can affect and be affected by icings: their seasonal persistence, their melting behavior, and the volumes of water release. We complement these observations with quantitative analysis through the Difference of DEMs (DoD).

Changes within the proglacial area were quantified through multi-temporal terrestrial laser scanning (Fig. 3). Terrestrial LiDAR is a powerful measurement technique for observing geomorphological change [38]. Point cloud data were acquired from the summit of Haavimbjället at an altitude of 783 m.a.s.l in April and September in 2016, 2017, 2021 and 2022 using a Riegl VZ-6000 [39]. This location was selected because the whole watershed can be observed from source to sink with minimal shadow effects in the data. The 1064 nm wavelength laser allowed strong reflections from all types of surfaces such as rocks, debris, ice and snow surfaces during scans. The LiDAR data was georeferenced and registered using an Iterative Closest Point Algorithm using the Riegl RiSCAN Pro [40] software with the available 5×5 m DEM from 2012 [41] serving as a reference. Rasterization of LiDAR data was done with the CloudCompare software for a resolution of 1×1 m [42], resulting in a Level of Detection 95% of < 0.12 m for the moraine area.

The DoD between the consecutive spring and autumn campaigns shows large-scale evolutions of the moraine topography. It enables the measurement of both accumulation and depletion of ice bodies (i.e. icings), stored in the main river system within the proglacial area (Fig. 3). The DoD allows for quantification of both ice thickness and snow depth over the moraine. Furthermore, we can deduce the volumes (ice + snow that correspond to a water stock) that fill the canyons of the hydrographic system during winter and spring.

Field observations, supported by the analysis of automatic photo station images, suggest that icings are a recurring feature of the riverbed. The overall shape of these icings, including their internal structure, will provide insights into their evolutionary dynamics and influence on flow. This statement is assessed when analysing GPR radargrams.

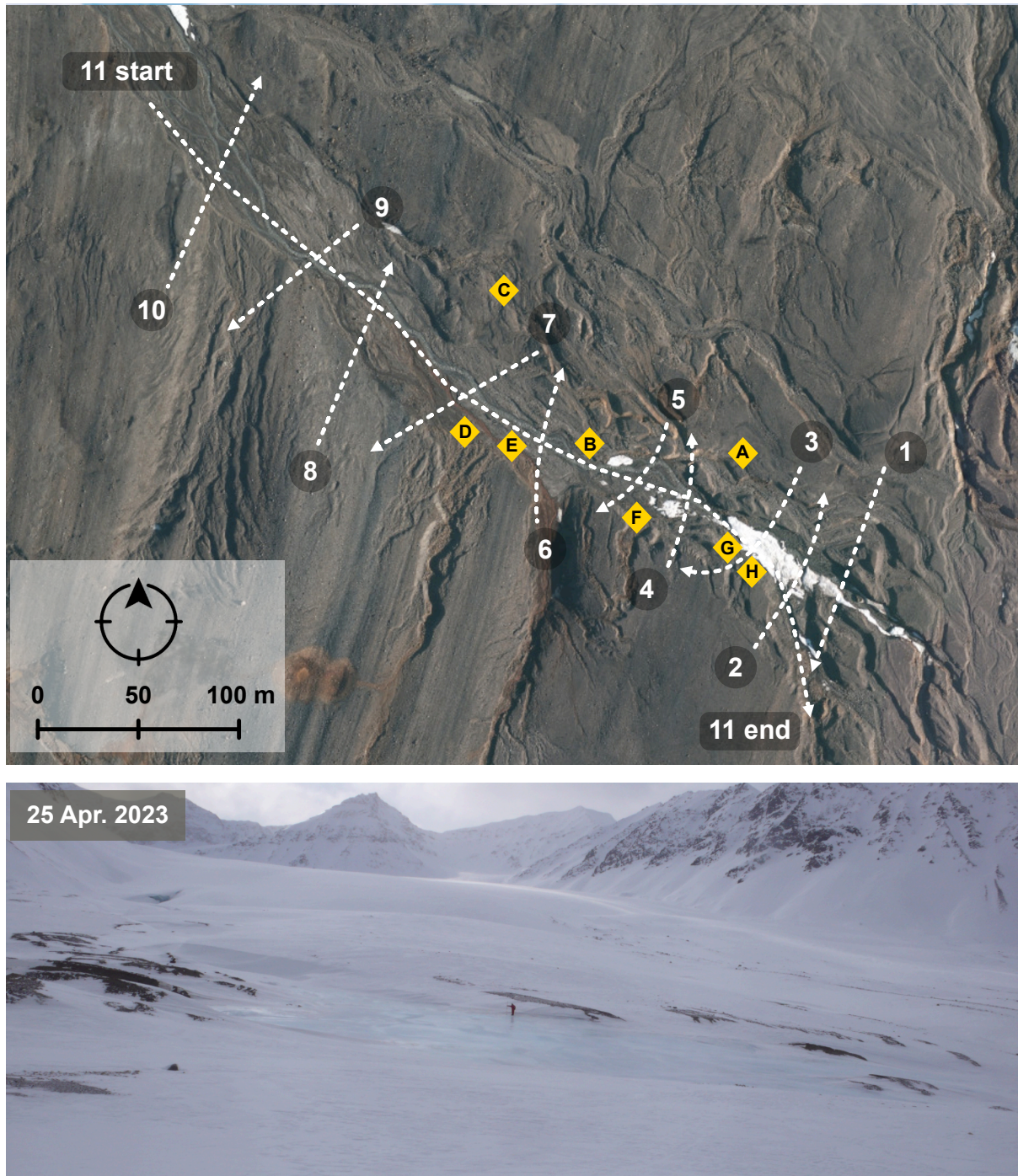


Figure 3: Top: the background aerial photography (Toposvalbard, Norsk Polarinstitut) highlights the geographical context, including the remaining icings, of the investigation site. All GPR transects are represented on the map, with an arrow indicating the direction of the measurement. Letters indicate the location of each photo taken on the ground in autumn and reported in Fig. 5. Bottom: picture of the studied icing taken in April, with a person providing the scale of the scene.

3.3 Ground Penetrating RADAR

If surface processes could easily be studied within the methods described in sections 3.1 and 3.2, we are also interested in the unseen icings' internal structure as well as depth and ground types, extrapolated from surface observations to sub-surface interfaces. Indeed, the main factor that caused the most significant change in the moraine morphology was the alteration of the riverbed due to the presence of icings, blocking the original channel. Thus, we investigate the inner structures of icings using GPR. This investigation was completed by walking over the icings along the tracks exhibited in red on Fig. 1 and dashed lines on Fig. 3, pulling a 500 MHz center-frequency shielded antenna and collecting the echoes using a Malå ProEx GPR control unit with custom software available from <https://sourceforge.net/projects/proexgprcontrol/>. The time-dependent A-scan are converted to depth-dependent traces assuming a homogeneous ice medium relative permittivity of 3 leading to an electromagnetic velocity of $170 \text{ m}/\mu\text{s}$. No processing other than removing the mean value of the whole B-scan 2D image and applying a fast-time linear gain was performed for analysis and the figures displayed in Figs. 4 are the raw signals. The even traces were flipped along the slow-time axis to provide a consistent X-axis with respect to the odd traces.

The 3D map of the profiles displayed using OpenDtect (<https://dgbes.com/>) over the geographic settings is shown in Fig. 4, with the eastern-most upstream area of the map holding the deepest part of the icings with most internal structures, and the western downstream part being shallower plains where the icings expand with little inner structure from GPR measurements. The 3D presentation of the transects allow for assessing the consistency of the features observed along the different intersecting transects, but leads to a cluttered static image. Hence, Fig. 4 (top) emphasizes the two most relevant transects in the deepest areas of the icings including the most significant reflectors observed during this measurement campaign.

4 Results

Field observations and photographic analysis (Fig. 2) reveal the process of icing formation and growth during the spring months, ultimately culminating in their complete disappearance before the end of the hydrological season.

The different pictures taken along the river course (Fig. 5) highlight the shape of the canyon when it is free of snow and ice, at the lowest water level at the end of the hydrological season. There are no icings residues remaining, and the main characteristics that emerge are a sharp-cut valley upstream, with unstable sediments and steep banks, while the downstream topography is much flatter and the riverbed

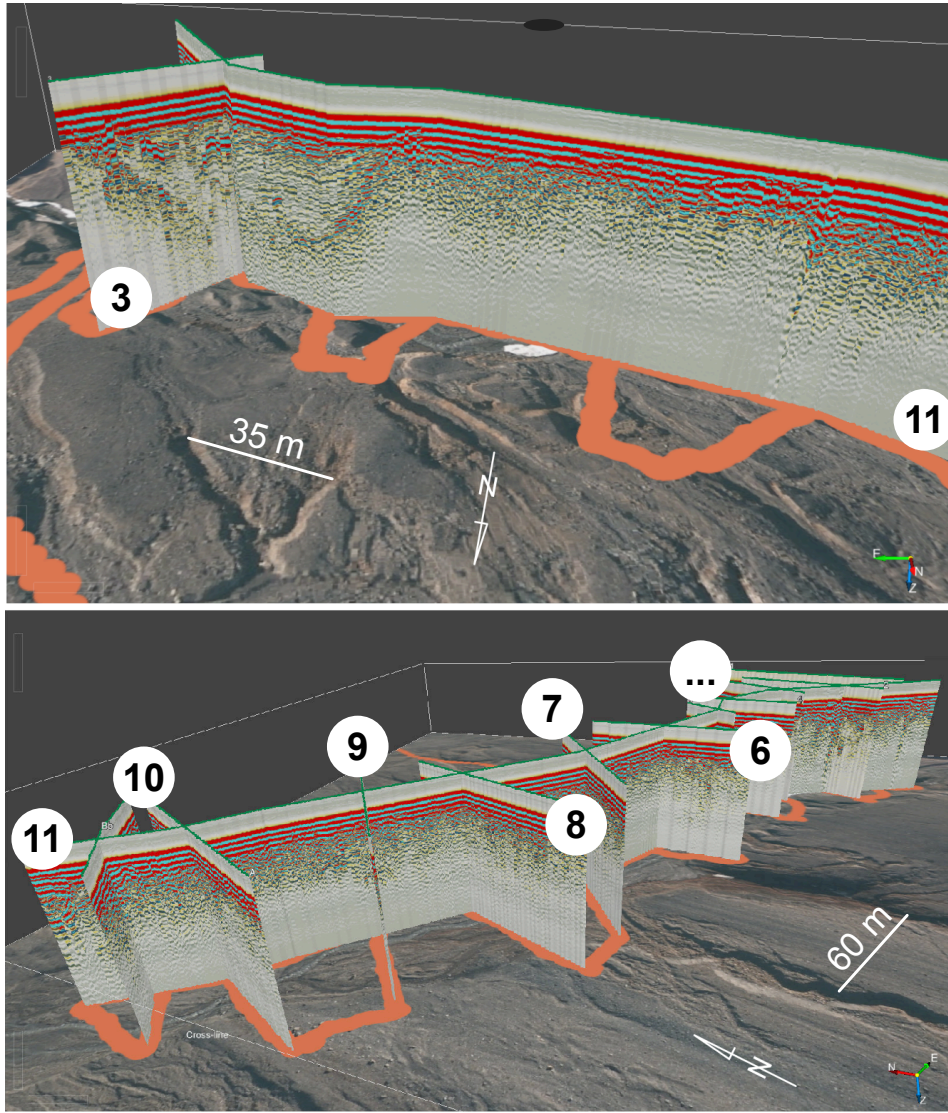


Figure 4: 3D maps of the profiles collected using GPR overlaid on an aerial photograph providing the geographical settings of each acquisition. Bottom: all GPR measurements are displayed in their geographical context. Top: only transects 3 and 11 including the deepest and feature rich part of the icings are displayed, emphasizing the consistency of the sub-surface layering observed during both measurements. Scales on an oblique view image vary with depth: the distance between geomorphological features identified on an orthorectified aerial photograph provide a sense of the scale. GPR radargrams are displayed in decreasing order from foreground to background and the “...” mark continues the number series.

is wider with large blocks. We will identify:

- upstream (Fig. 5, pictures A, B, F, G, H), a confined riverbed that concentrates all flows and promotes powerful discharges with strong river incision.
- downstream (Fig. 5, pictures C, D, E), a braided hydrographic network whose shape promotes diffuse flows that spread across the width of a less pronounced alluvial riverbed characterized by



Figure 5: Different views of the canyon and the outwash plain where a massive icing takes place every winter. Upstream, the height of the cliffs defining the canyon can reach several meters. Even on the outwash plain, the roughness is significant (> 1 m) but filled with ice during winter. While icings could persist throughout an entire summer season, in recent years, they have completely melted by the end of the summer. Each letter refers to the location displayed on Fig. 3.

terrace scarps.

In the moraine upstream zone, under drift-mantled deposits (Fig. 5, pictures F and G)), successive discharges and runoffs shape the topography with channels becoming deeper (Fig. 5, picture A). There-

fore, streams are gradually concentrated in a single deep riverbed and abandon paleo-stream channels (Fig. 5, picture B).

In the moraine downstream zone, floodwater passing over icings tend to erode the banks laterally and produce wide, shallow, river channels as observed (Fig. 5, pictures C, D and E). The transition from upstream sharp banks to downstream wide riverbed is gradual as visible on Fig. 5, picture H.

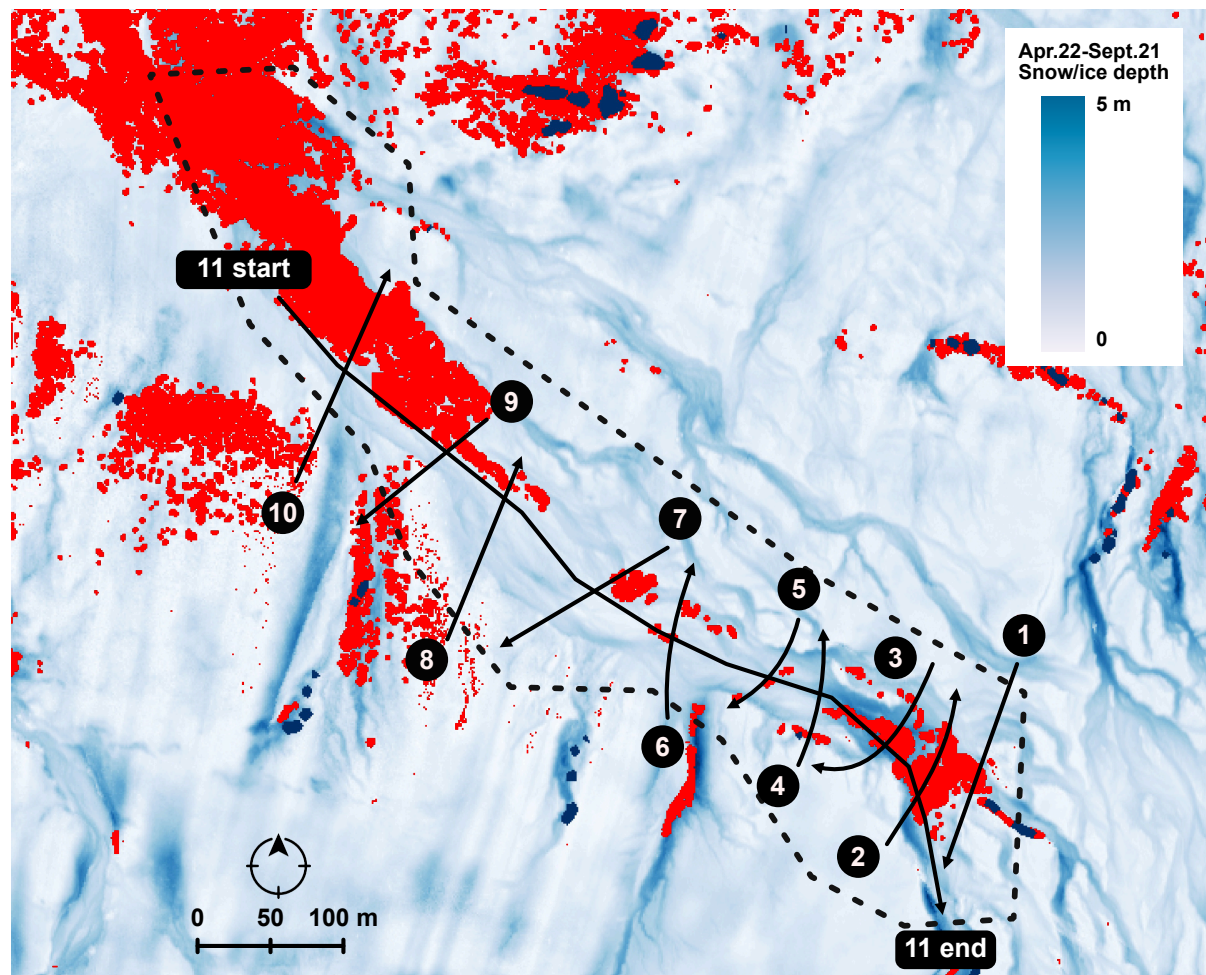


Figure 6: April to September DoD without interpolation, with red areas highlighting the pixels where no LiDAR measurements were recorded in April. Indeed, while the moraine is dry in September, the wet areas of liquid water covering the icings in April prevent backscattered light from reaching the LiDAR, displayed as red areas in this map. The dashed polygon delineates the icings area for computing its volume.

The DoD from April to the former October (Fig. 6) highlights the large amount of snow and ice stored in the active canyons of the main glacial river. Combining snowfalls, wind effect and water upwelling events, all canyons are filled, with a depth that can reach almost 5 m. The depth of the canyons correspond to the maximum height that the layer of ice and/or snow can reach. Indeed, since the surface of icings is most of the time bare ice with liquid/frozen water, it is difficult for the snowpack to maintain itself. Regarding the outwash plain, we have delineated a polygon encompassing the majority

of the downstream icing in order to calculate the stored equivalent volume in water (Fig. 6, dashed line polyon). The icing in itself, represents a surface of 85,000 m² for an estimated volume of 10⁵ m³ of ice, equivalent through the ice density of 0.92 to 0.92 · 10⁵ m³ of water equivalent. In order to provide a scale of magnitude, according to meteorological data recorded at Ny-Ålesund weather station (8 m above mean sea level, 5 km west of AL) and published on the `seklima` database, a precipitation sum of 370 mm fell during 2022. This quantity integrated over the 10.5 km² basin leads to 3.9 · 10⁶ m³: the contribution of this icing in freshwater represents 2.4% of the global precipitation.

The B-scans of all GPR transects are detailed in Figs. 7, 8, 9 and 10 from one bank to the opposite bank, and Fig. 11 for the transect along the icing. Each radargram is compared to the DoD cross section along the corresponding track, with corresponding features highlighted with arrows linking both datasets. Each radargram with even index, and associated DoD cross-section, was flipped along the scan direction to provide a consistent abscissa starting from the northern ridge. Finally, features visible from the surface during GPR acquisition have been annotated on top of each radargram, with vertical dashed lines separating the various zones (snow, ice or rock) as seen from the surface. Ice domes (Fig. 12, top) are a characteristic feature of icings where pressures pushes liquid water through the icing, generating enough force to raise and break the ice surface, leaving liquid water flowing despite negative temperatures. This liquid water impacts the GPR emitted pulse by raising the permittivity of the medium surrounding the transmitting antenna and lowering the pulse center frequency since the bowtie antenna operates at fixed wavelength when polarized by the avalanche transistor in the used setup. Furthermore, high permittivity media focuses electromagnetic power towards the ground through its higher capacitance, as seen in transect 1 (around A-scan 280) and transect 2 (A-scans 150 to 180 and around 350).

Fig. 11 exhibits some striking features about abscissa 1500 of the radargram, which are interpreted as ice layering since measurements were performed on bare ice (no snow accumulation) and pictures G and H from this area on Fig. 5 indicate that sediments would not be able to accumulate from one melt season to the next.

Various features are identified from their reflected echo polarization. A detailed analysis of radargram 3, especially around A-scan 150, confirms the relationship between surface water flow, mapped by the absence of LiDAR backscattered signal, and internal structure of the icings. Indeed, the polarity of the backscattered wave detected by the GPR informs on the relative permittivity of the interface reflecting the electromagnetic wave with respect to the surrounding medium. In Fig. 12, a polarity inversion as observed on the area surrounded by the blue ellipse indicates a wave reflected by a high permittivity medium such as a water-filled void. In this analysis, the direct wave used for reference displays a copy, as seen by the receiver, of the signal broadcast by the emitter, with a time delay defining the reference 0-depth. The antennas are considered in close contact with the ice and the pulse propagating into

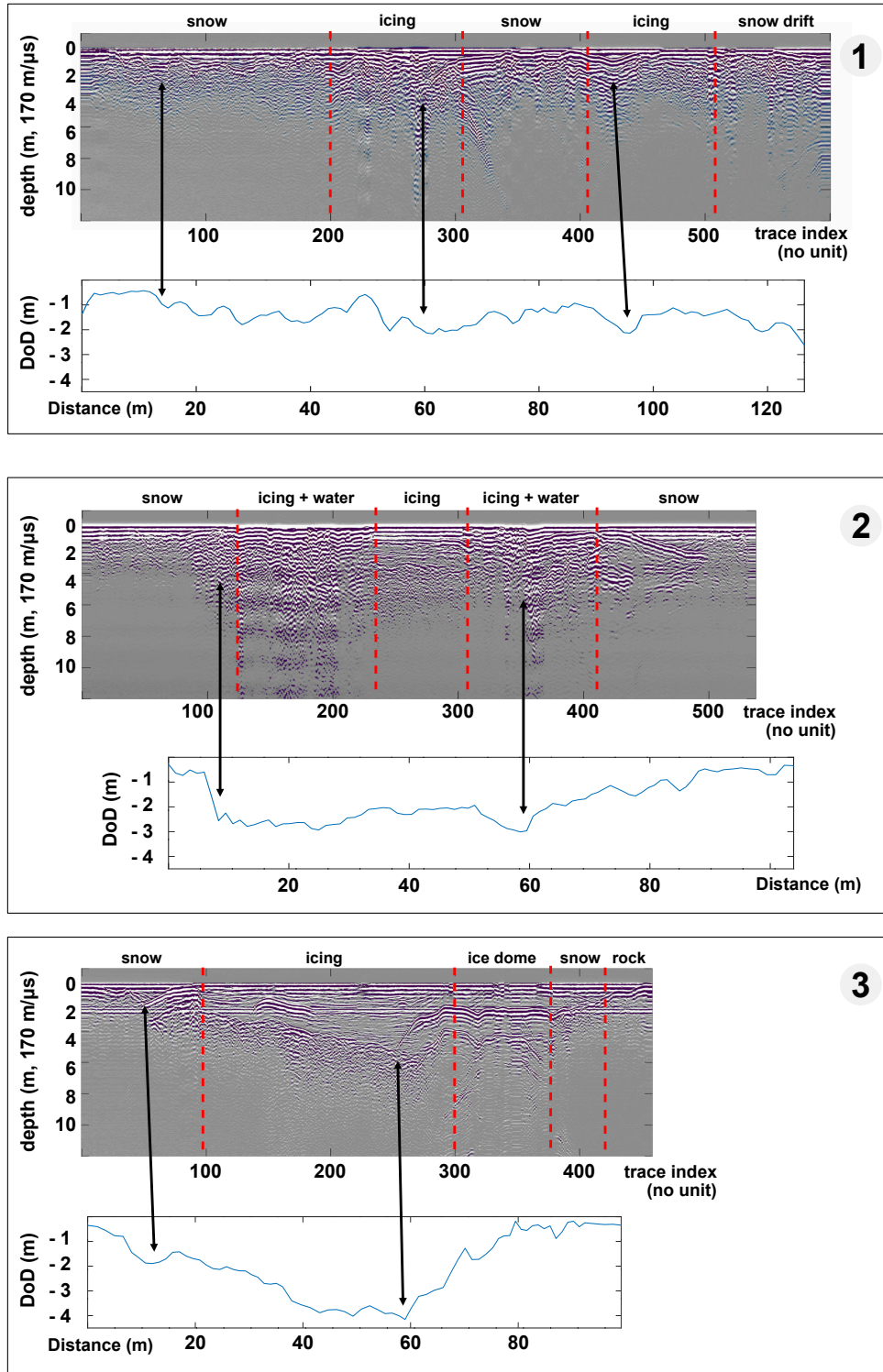


Figure 7: GPR profiles 1 to 3 (top) and corresponding DoD transect (bottom) with arrows highlighting some of the most striking matching features. The structure of a thick upstream icing which is strongly constrained by the topography of the riverbed is visible. Red vertical lines and annotations on top of each radargram correspond to features visible from the surface during the measurements.

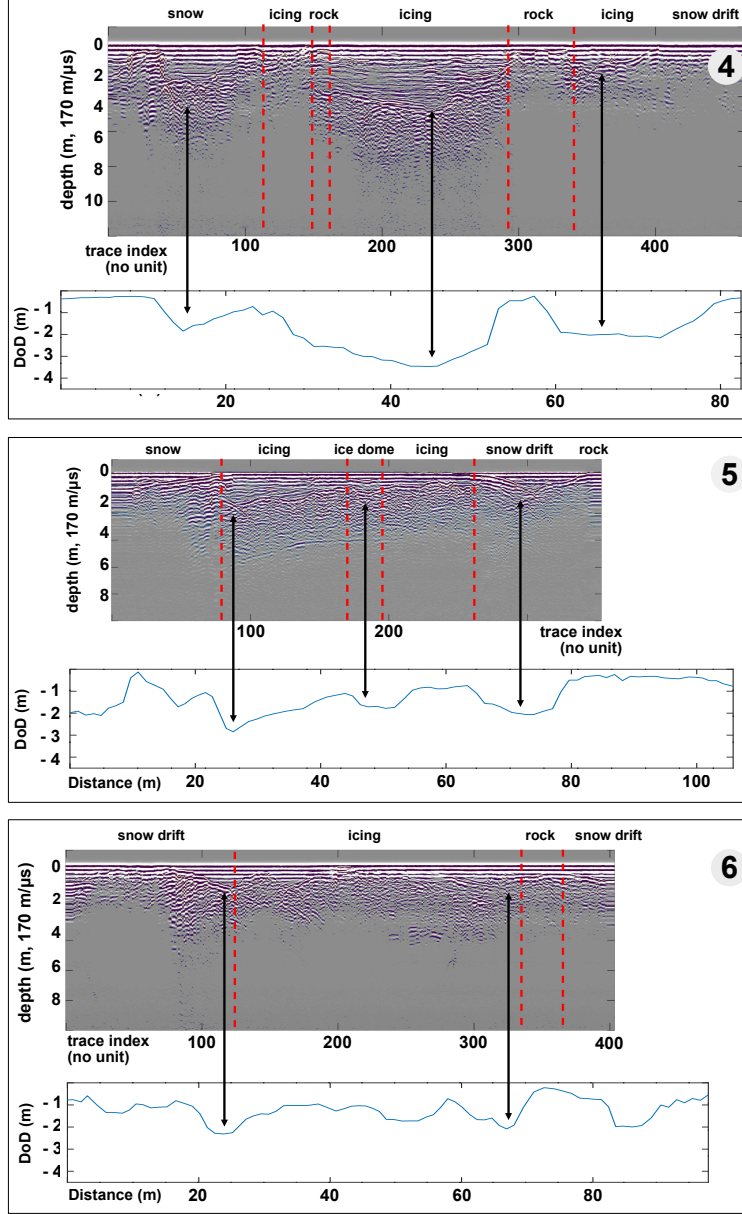


Figure 8: GPR profiles 4 to 6 (top) and corresponding DoD transect (bottom) with arrows highlighting some of the most striking matching features. Banks become less pronounced as the measurements are continued downstream. Red vertical lines and annotations on top of each radargram correspond to features visible from the surface during the measurements.

the dielectric medium (ice) exhibits the same polarity as the direct coupling surface wave. When an electromagnetic wave reaches a dielectric interface[43, 44], the reflection coefficient

$$R = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}}$$

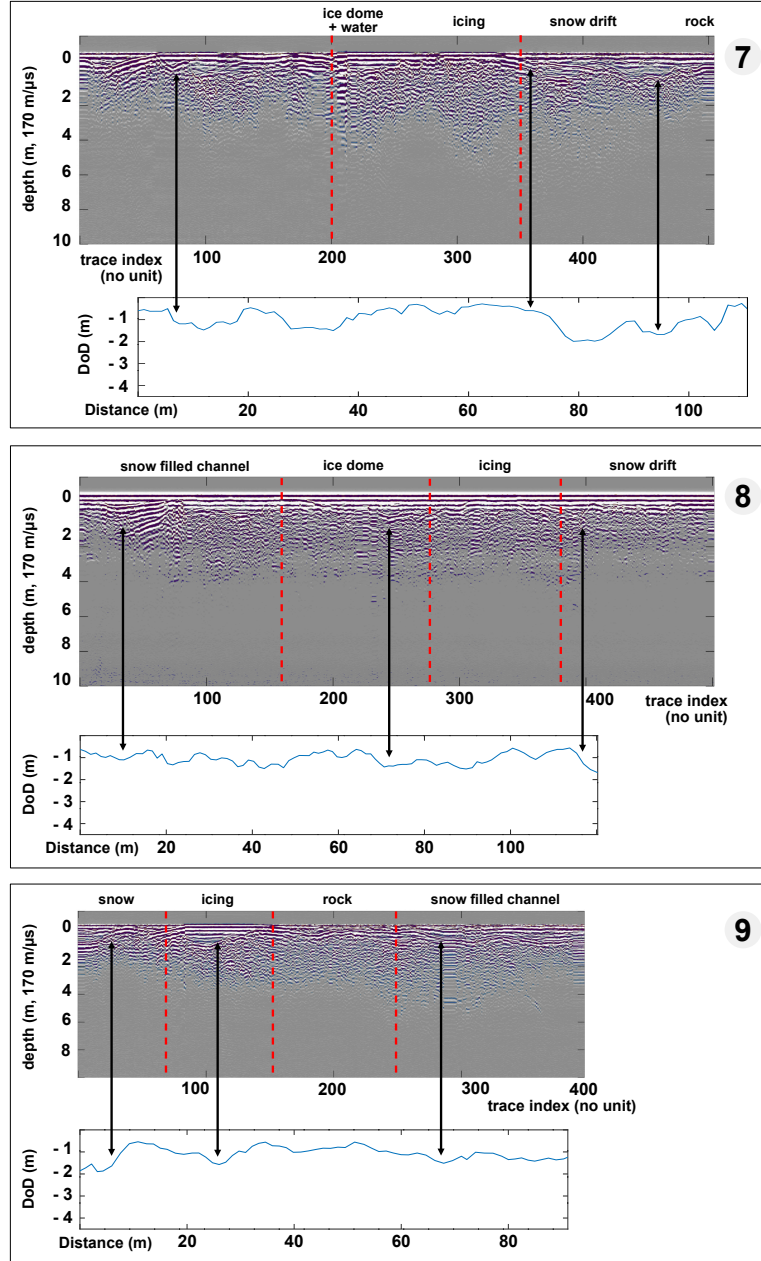


Figure 9: GPR profiles 7 to 9 (top) and corresponding DoD transect (bottom) with arrows highlighting some of the most striking matching features. The topography becomes flat downstream in the outwash plain. Red vertical lines and annotations on top of each radargram correspond to features visible from the surface during the measurements.

becomes negative if the second medium reached by the wave exhibits higher permittivity ε_2 than the incoming medium 1 with permittivity ε_1 . Thus, ice-air interfaces exhibit no phase inversion (green ellipse) while the ice-water interface does exhibit an inversion (blue ellipse). The central part of transect 3 around traces 200 to 250 appears as devoid of internal structure and is interpreted to be solid ice. Still

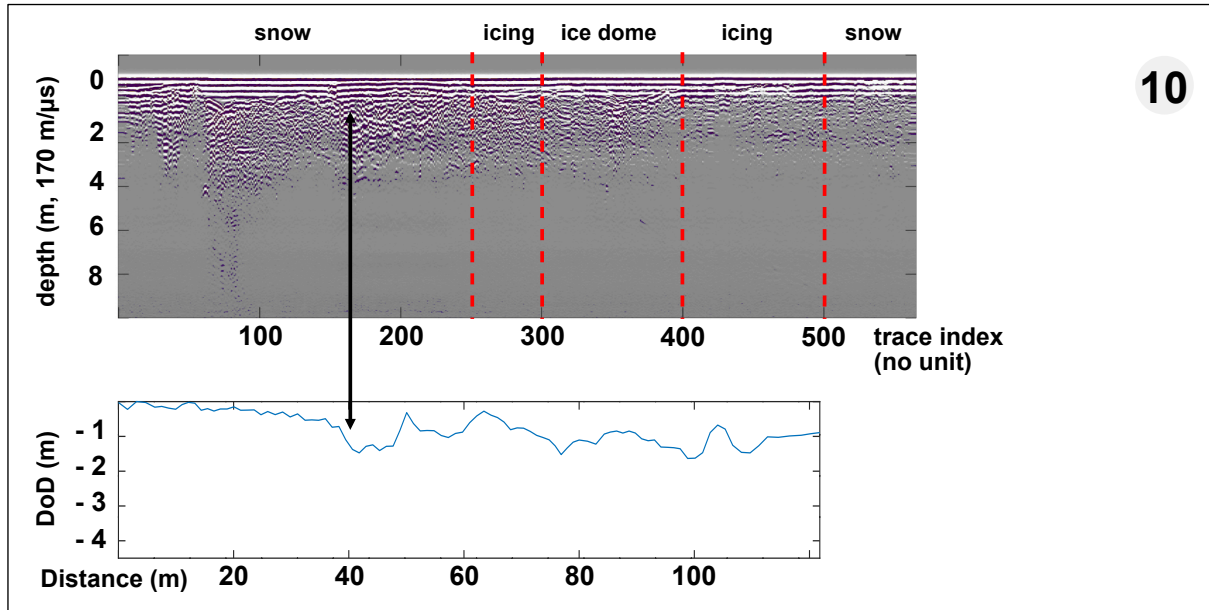


Figure 10: GPR profile 10 (top) and corresponding DoD transect (bottom) with arrows highlighting some of the most striking matching features in the outwash plain. Red vertical lines and annotations on top of each radargram correspond to features visible from the surface during the measurements.

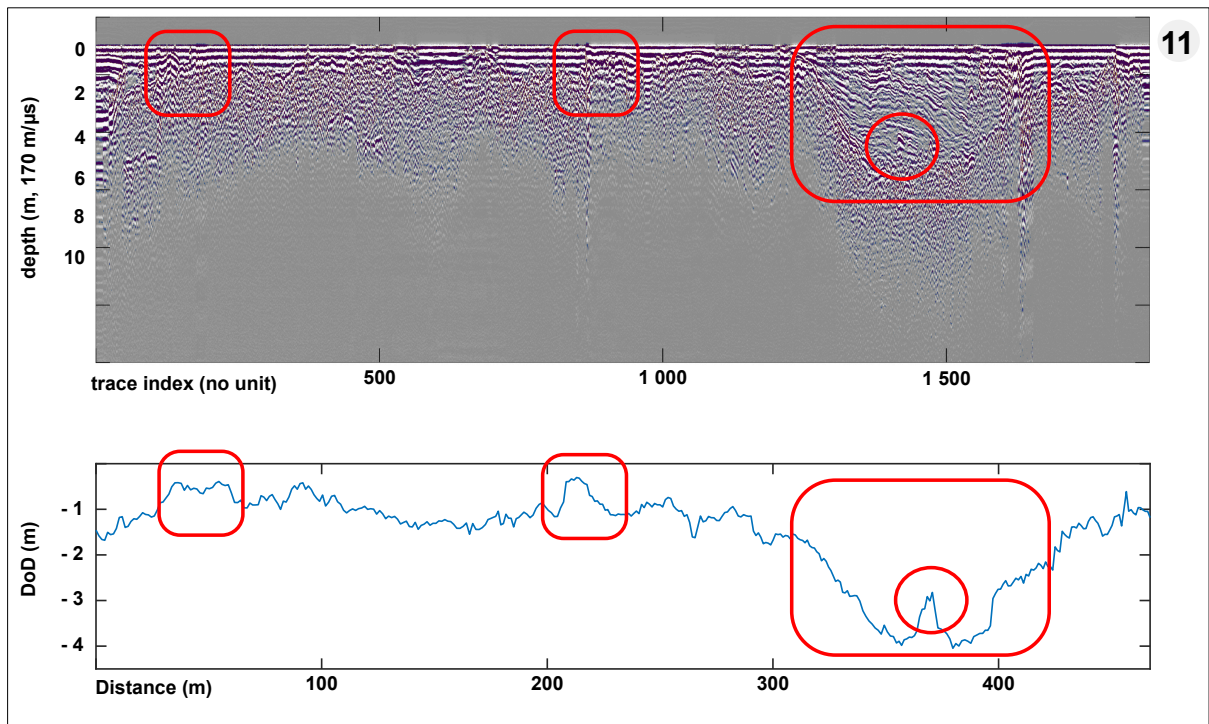


Figure 11: GPR transect along the icing length (top), from downstream (left) to upstream (right) and corresponding DoD transect (bottom). Red rectangle and circles highlight some of the striking matching features on both datasets. The measurement was completed on bare ice and no surface feature worth mentioning is included in this chart.

225 concerning transect 3, around trace 300, the polarity of the echo generated by the internal structure is
 226 maintained between incoming and reflected waves, hinting at a high permittivity reflector we attribute to
 227 liquid water since such stream has been observed on the surface during the measurements. Furthermore, a
 228 very high permittivity medium consistent with a liquid water filled channel, leading to a strong reflection
 229 coefficient, is attributed to this reflector since a double-transit echo hides the bedrock and is seen as
 230 a copy of the reflector at twice the physical depth of the interface. A liquid stream flowing over the
 231 bedrock is consistent with the continuity of the interface at the rightmost part of the transect where the
 232 interface reaches the surface at a location associated with the end of the icings during the measurement
 233 as determined when walking on solid rock moraine.

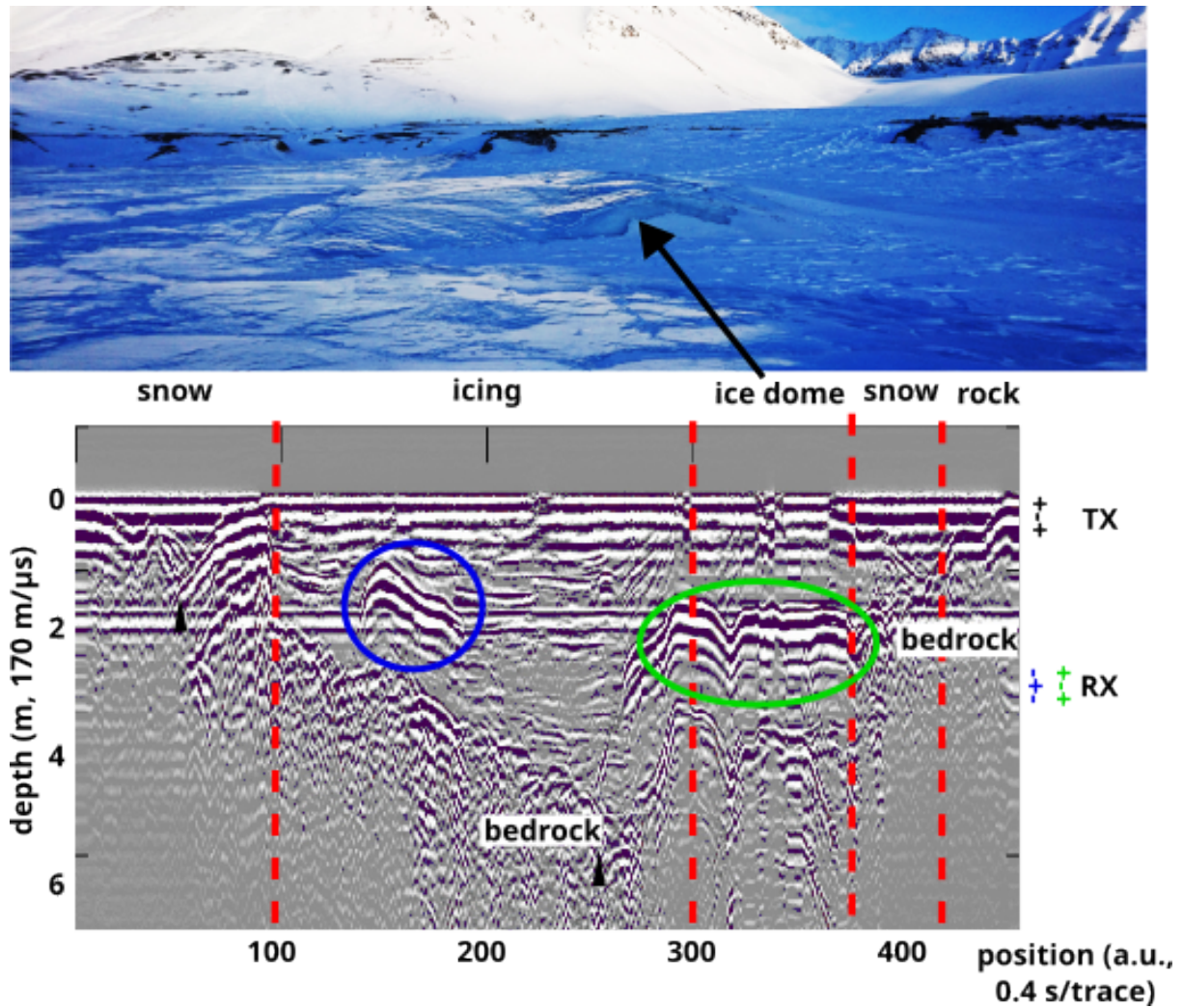


Figure 12: Zoom on radargram 3 where internal structures are best visible and easiest to interpret. When the reflected wave is the same polarity than the incoming wave, a **low** permittivity medium such as **air** was the cause of the reflection (green ellipse). When the polarity is inverted (blue ellipse), a **high** permittivity interface such as a **water** filled cavity was the cause of the reflection. Top: an ice dome protruding above the icing where liquid water is seeping despite freezing temperatures.

We interpret the LiDAR reflection map of Fig. 6 as a surface state resulting from internal icing structure, where water-free areas leading to detectable backscattered laser pulses are associated with water-tight densely packed ice zones, whereas water covered areas where no LiDAR backscattered signal was detected are associated with porous media where water filled channels bring liquid water to the surface. This water is kept in a liquid state despite freezing temperature with the high pressure as seen from the ice domes up to 1 m high protruding from the icings otherwise flat surface. The strong reflector described in transect 3 and attributed to a water filled buried channel where the polarity between incoming and reflected waves is maintained, is located at a position matching the surface observation of an ice dome where liquid water was seen to be seeping (Fig. 6, top). Ice domes are located downstream the channelized icings where liquid water can flow until it reaches the downstream damming effect of the dense icings. Water upwelling is observed on the surface where it seeps despite negative temperatures under high pressure.

5 Discussion

The analysis of GPR profiles (Figs. 7 to 11) highlights the structure of icings from which we can deduce how water flows into and underneath the ice, closely related to the morphology of the channels upstream and on the outwash plain. Indeed, it appears that the deepest and steepest parts of the channels host the thickest icing plug but with buried and/or underneath channels allowing water flow. Conversely, the thin icings area in the outwash plain are more compact i.e. frozen to the bed and directly connected with the ground. This configuration without subglacial channels make it watertight, and means that there is only a very limited space allowing for liquid flows.

Indeed the main originality of this work, over similar studies found in the literature extending on much larger areas, is the local investigation using in-situ measurements on a fine scale, as opposed to spaceborne remote sensing focusing on surface features but unable to penetrate the sub-surface structure of icings. Coarser DEMs such as the Arctic DEM provide neither the spatial nor the temporal resolutions needed to match this study. As illustrations of these differences, [45] considers a much broader area (305 000 km²) studied using historical topographic maps and satellite images in Russia, while [46] analyses icings in Alaska using multispectral remote sensing involving microwave synthetic aperture radar (SAR), infrared and thermal imaging collected by satellites. Neither C-band radar nor infrared/thermal imaging is able to penetrate the icings deep enough to identify internal structures. Similarly, [47] maps icing distribution over the whole North-Eastern Siberia area by analyzing satellite images. [48] provides a large scale review of icing distribution in Arctic regions and summarizes various measurement mechanisms, both on site and using remote sensing.

On the other hand, [49] reaches conclusions similar to ours on a broader scale with the migration of channels induced by icings, again using satellite images. Similarly, [50] proposes a physical model of icing formation including stream/groundwater interaction with the ice structures.

Besides the geological and morphological parameters of a glacier basin, there are two main factors that can play a role in the spatial evolution of such proglacial hydrosystems over time. The first factor is the retreat of the glacier snout which is exposing new areas that can influence flows in various ways. The retreat is also changing the location of the main outlets, and it is sometimes removing glacier ice dam effects, which can lead to significant changes in the organization of the flows. The second factor is icings.

Icings are initially formed in active channels and might play a significant control on liquid flux processes by interacting with runoffs and lead to seasonal oscillation from one riverbed to another. Once streams are diverted, water carves the alternative riverbed until it might become deep enough for the stream to no longer reach the icings which end up melting and not forming in subsequent years due to the absence of water.

It has been previously noted that icings act as successive dams, limiting the flow of liquid due to their spatial extent. This study further observes that the hydrographic network is organized as if there were multiple dams on the riverbeds. A key point to consider is how the 3D structure of icings contributes to this “dam effect.” Upstream icings allow liquid runoffs to flow between the icing base holes and the riverbed, while downstream areas lack this space. Consequently, the downstream areas remain flat, leading to diffused runoffs, while the upstream channels continuously deepen. As a result, the active part of the hydrographic network becomes more active, causing erosion in the same riverbeds and making it difficult for the fluxes to change paths. The balance that could have previously existed between different riverbeds is now almost impossible. Stable areas become increasingly stable, while the active hydrographic network experiences constant reshaping. Although the moraine has long presented hydrological activity distributed across its entire surface, only a few areas are now very active. This creates a strong spatial heterogeneity, with very active areas that concentrate all of the hydrological processes and stable areas that can be qualified as paleo-glacial.

While ground-based oblique view cameras have been installed for long-term monitoring of the moraine evolution, the grazing angle is poorly suited for an overall visualization of the whole basin. However, opportunistic aerial pictures collected on the way to Ny Ålesund from August 2012 to 2016 as illustrated on Fig. 13 appear well suited for discussing the results. These pictures highlight the alternation of the hydrographic network depending on the year considered. We interpret these changes as being due to the presence/absence of icings acting as dams, themselves controlled by the melting conditions (intensity, duration that favor significant flows).

The main glacier river outlets exhibit significant channel network reorganization:

- upstream, the stream flow has been subject to deviation due to an icing plug located between the glacier front and the proglacial moraine on several occasions, leading to streams shifting between a channel in close proximity to the eastern external moraine and another new channel carved in the loose and unconsolidated material exposed by the glacier retreat (appendix A). As a demonstration of this evolution, in 2014, right at the eastern end of the glacier snout, the retreat of the glacier started to allow moderate amounts of the water from the main glacial river channel to flow west into a rather flat area of the inner moraine. In 2015, a combination of an icing plug and glacier retreat caused the glacial river to shift westward and towards the central part of the moraine. As a result, the stream dug a new channel in the fine-grained sediment of the moraine. At the start of the 2016 melt season, the stream temporarily flowed back into the old channel due to another icing plug in the new channel. However, by August, the plug had melted enough for the stream to flow again in the new channel. Since then, all outflows have been in this new riverbed (appendix B). The old stream-channel is now abandoned,
- downstream, a large icing dam that survived well into the melting season diverted water that was usually driven towards the western river towards the eastern river. Year 2013 (Fig. 14) was exceptional with the downstream icings surviving the whole melt season and preventing most of the flow from reaching the western outlet. This has only been witnessed once in the last 15 years of observations.

These considerations on the icings driving the flow towards one channel or another differ from the discussion about the distribution of water within the porous parts of the icings as observed from GPR analysis. When controlling the stream flow between the riverbeds, the icings are considered as watertight boundaries preventing the liquid water from reaching the plugged riverbed, since even a local watertight volume is enough to prevent the river from continuing its path beyond the icing. Hence, icings can act at two different levels: as watertight dams driving the main river flow from one canyon to another during the melt season, and on the other hand as a partly porous medium allowing water under high pressure during the freezing season to seep to the surface through cracks ending on the surface as ice domes.

This analysis confirms that in the current context, the increased role of the hydrological control on glacierized catchment (e.g. in the water circulation) is closely linked with the expansion of glacier's forefields. Based on our investigations, we believe that icings are now major proglacial formations that control the source-to-sink water cycle i.e. between glacierized regions and the shoreline. Indeed, although flow patterns are generally stable during the melt season, the two pictures in Fig. 15 demonstrate how upstream icings have control over water flow: even small changes in their elevation or general shape

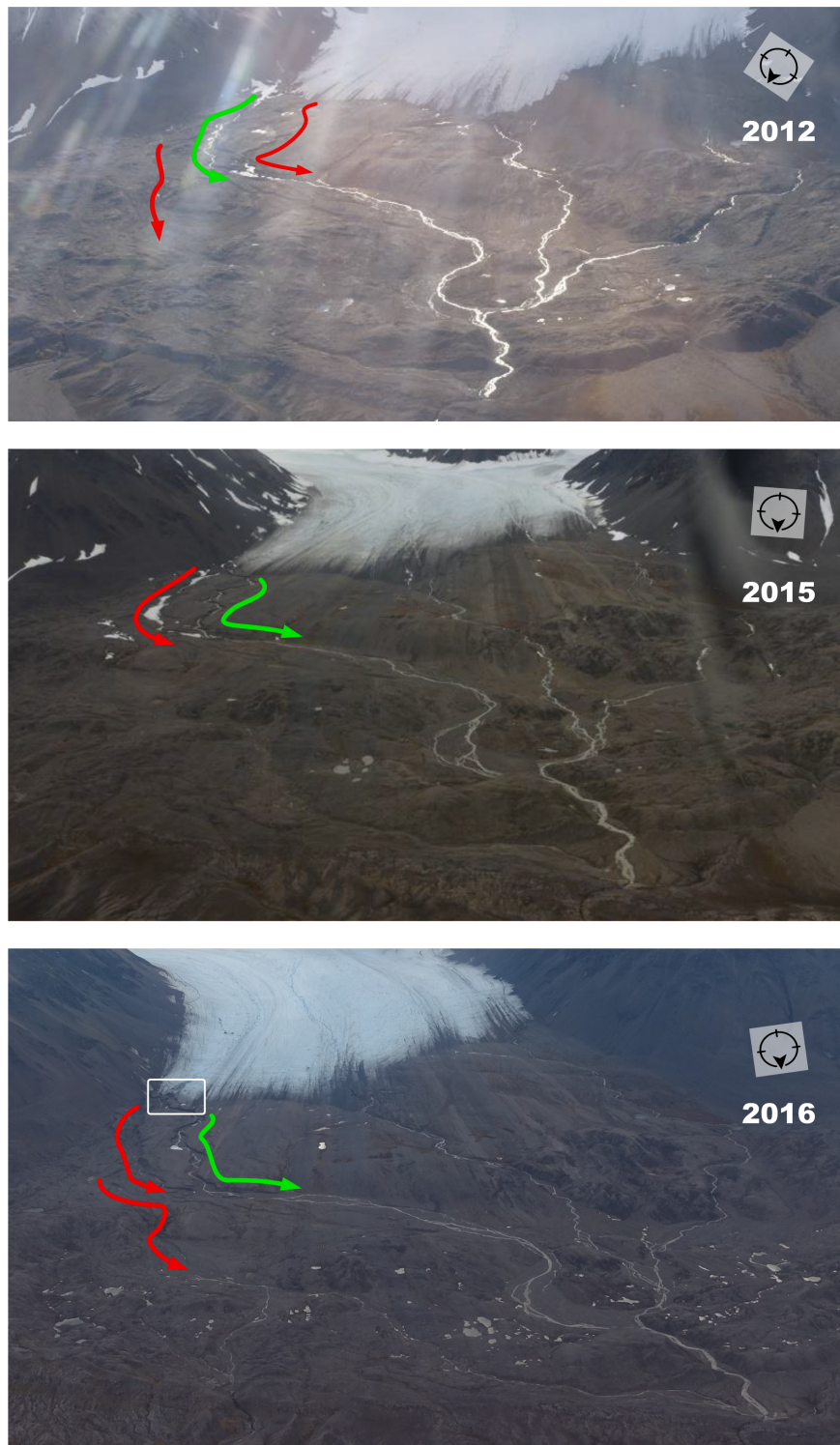


Figure 13: Opportunistic aerial images of Austre Lovénbreen collected between 2012 and 2016 illustrating the evolution of the flow depending on icing blocking conditions. The arrows guide the eye towards active water flows (green) and inactive channels (red) with the direction of flow determined by the arrow head. The square on the bottom figure highlights the location of the main glacier outlet. Note on the 2015 image the significant amount of leftover icings in the now inactive channel right of the red arrow.



Figure 14: Opportunistic aerial image of Austre Lovénbreen collected in 2013 illustrating the impact of upstream and downstream icings (white squares) driving all water flows to the eastern outlet rather than the western outlet collecting all outgoing water streams as seen on Fig. 13. The arrows guide the eye towards active water flows (green) and inactive channels (red) with the direction of flow determined by the arrow head.

can importantly impact the overall fluxes through their dam effect. Within a few days between the two observation dates, the main outflows from the glacier shifted from one channel to another.

This strong correlation between water flow and minute topographic variations is highlighted in (appendix 17) when we model flow from DEM analysis. Therefore, we conclude that both melting icings and changes in icing structure redirect water flow and shape the hydrological response downstream. At present, the old abandoned channel network cannot be reached since its level has become higher than the current riverbed. Thus, it appears that icings can now only be formed in the active channels, and no longer alternatively as they did before.

The latest investigations using GPR have provided an opportunity to study and understand the internal structure of the icings formations. Fig. 16 highlights the findings. The B-scans indicate a change in the ice structure from upstream to downstream, with fewer distinct structures and a more compact ice volume downstream. This suggests that the compactness of the downstream ice formations contributes to flooding effects, while upstream, the underground pipes and caves provide optimal conditions for riverbed excavation. These ice formations have a bumpy shape, resembling a protective layer for the underlying water flows. They function in a similar way to a karstic system, where the glacierized roof of an under-ice void or cave can collapse suddenly, altering the course of the river. As the running water erodes and deposits sediment, it shapes the ground surface.

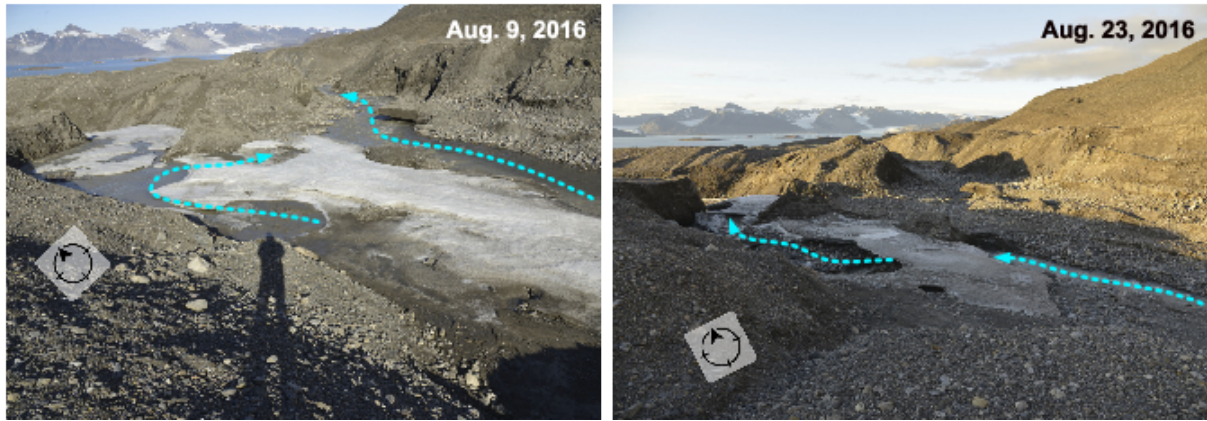


Figure 15: Two pictures taken at the glacier outlet at close dates highlight the toggling of the water fluxes, controlled by the icing structure acting as a dam. Within days, the water stream switched from a channel to another only according to the icing structure change.

In contrast, the compact ice formations contribute to a damming effect and the up-welling of liquid water, even in negative air temperatures. The refreezing of liquid water results in the formation of a micro topography that exhibits characteristics akin to a “stair-step” arrangement. It exacerbates the dam effect by acting as a series of small cascades where surface water refreezing contributes to the growth of the icing structure. Consequently, the elevation of the ice formations exceeds that of the river banks.

At times, water can also become trapped beneath these compact ice structures, leading to the formation of pressure cracks on the surface. These cracks are frequently observed in downstream areas during the spring season. Here, the pressure is supposed to be maximal. Consequently, as in the previous case, liquid water is expelled even at temperatures below 0°C , causing the enlargement of the ice dome. This phenomenon thereby creates a lasting structure within the riverbed, which regulates the river flows and is likely to cause flooding across the entire flat intra-morainic plain.

Eventually it is important to keep in mind that icings are dynamic features that go through different phases during the season. Early on, surface temperatures below zero and low or moderate liquid flow rates lead to their formation. As temperatures and flow rates increase, icings are affected, shrinking both on the surface and at their base, and becoming more permeable in the process. During this transition period, icings can gradually lose their damming effect but keep on acting on outflows as a gate that will limit the amount of water that can go through and potentially divert some of it. Ultimately in full summer conditions, high temperatures and flow rates will lead to their complete melting and remove any remaining constraining effect on the hydrological network. Yet, all changes that occurred in the channels in a given year will directly impact the location, magnitude and therefore subsequent role of icings for the next year.

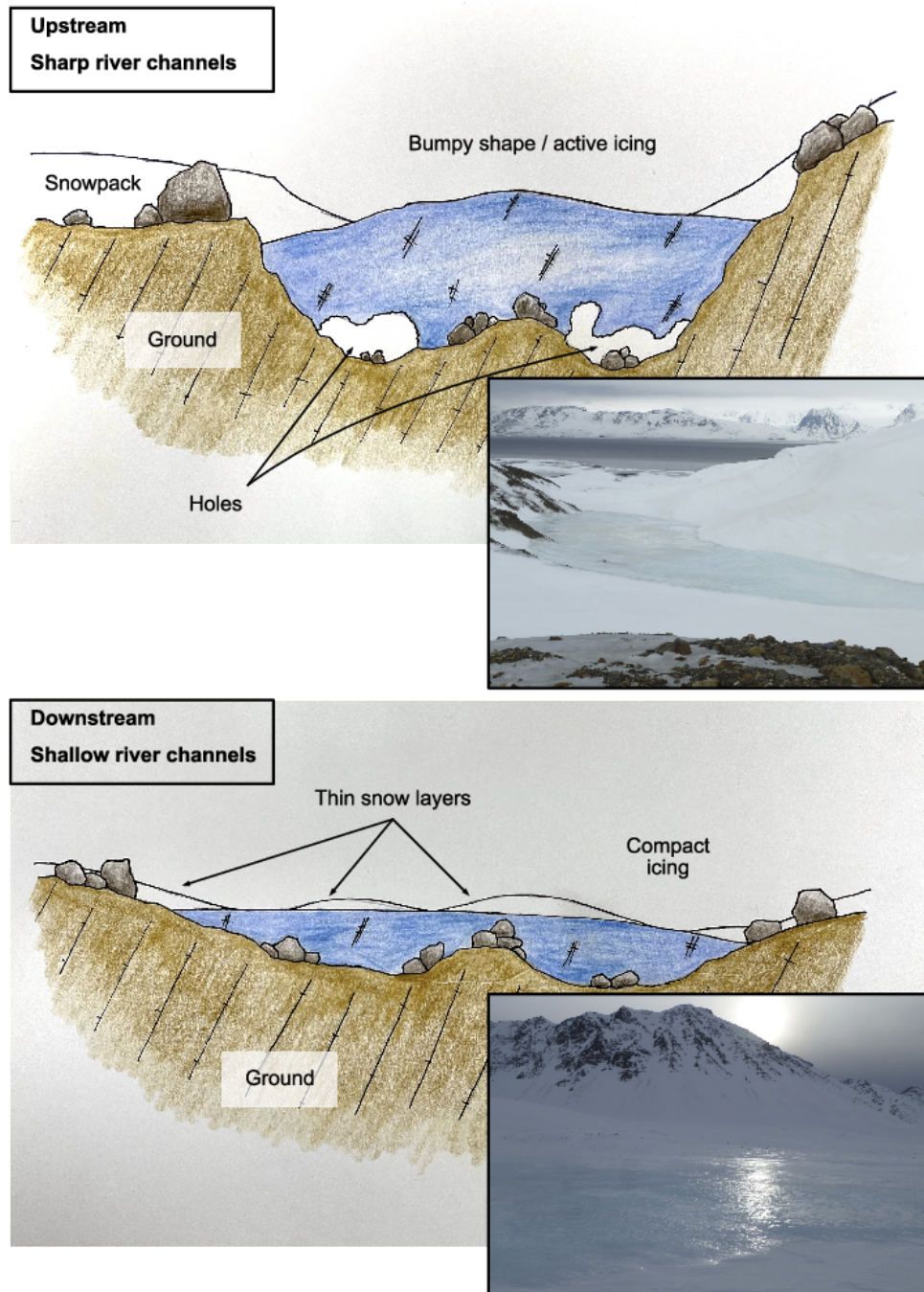


Figure 16: Radargrams have made possible to draw a sketch of the real profile. Upstream, icings structure is scrappy with several holes, caves and pipes allowing water to pass through (especially during melting season). Downstream, icings are way more compact, favoring water upwellings and liquid outflows even along with negative temperature. This process gives a “stair” shape and more broadly a dam effect.

6 Conclusion

In this paper, we have investigated the impact of icings on shaping the hydrographic network of a small Arctic glacier forefield by examining original data collected from the Austre Lovénbreen moraine

in Svalbard between 2012 and 2022, complemented with a 2005 Digital Elevation Model. This study specifically examines the response of the periglacial environment to glacial retreat and increased runoff. Optical timelapse and opportunistic photography qualitative observations were complemented with LiDAR Digital Elevation Model for quantitative surface investigations. GPR aimed at mapping internal structures and relating sub-surface features with surface water seepage identified on the surface with the absence of reflected signal during LiDAR mapping. Sub-surface ground interfaces are compared with difference of Digital Elevation Models updated yearly from LiDAR measurements.

The analysis of these data over different zones of the moraine shows differences in behavior between the upstream and downstream areas of icings. Upstream, icings function like a karst system due to their internal structure, with pipes and holes controlling the runoffs. Downstream, the compact icings result in different dynamics, combined with wider and anastomosed riverbeds that control more dispersed fluxes. Icings act as dams controlling which riverbed carved in the loose material newly exposed by glacier retreat is followed by the main glacier river outlet. Since icings can only be formed where water has been flowing during the previous melting season, an oscillation between two channels was observed for several years, until one of the canyon level was lower enough with respect to the other to be the only one used by the river, leading to a stabilization of the hydrographic network. We thus deduced the processes by which an icing modifies and controls the hydrographic network by influencing surface flows within the moraine.

Acknowledgement

This work is supported by a grant of the Franche-Comté county (France) and the French National Research Center (CNRS) MITI grant, as well as the French Paul-Émile Victor Polar Institute IPEV, under the PRISM grant.

Data availability

Data is available on request from the authors.

References

- [1] R. Hodgkins, R. Cooper, J. Wadham, and M. Tranter. The hydrology of the proglacial zone of a high-arctic glacier (Finsterwalderbreen, Svalbard): Atmospheric and surface water fluxes. *Journal of Hydrology*, 378:150–160, 11 2009.

- [2] S.H. Mernild, G.E. Liston, D.L. Kane, N.T. Knudsen, and B. Hasholt. Snow, runoff, and mass balance modeling for the entire Mittivakkat Glacier (1998–2006), Ammassalik Island, SE Greenland. *Danish Journal of Geography*, 1946:121–136, 2007.
- [3] B. Barzycka, M. Grabiec, M. Błaszczuk, D. Ignatiuk, M. Laska, J.O. Hagen, and J. Jania. Changes of glacier facies on Hornsund glaciers (Svalbard) during the decade 2007—2017. *Remote Sensing of Environment*, 251, 12 2020.
- [4] A. Bartsch, M. Gude, and S.D. Gurney. Quantifying sediment transport processes in periglacial mountain environments at a catchment scale using geomorphic process units. *Geografiska Annaler. Series A, Physical Geography*, 91:1–9, 2009.
- [5] J.O. Hagen, J. Kohler, K. Melvold, and J.-G. Winther. Glaciers in Svalbard: mass balance, runoff and freshwater flux. *Polar Research*, 22:145–159, 12 2003.
- [6] D. Ignatiuk, M. Błaszczuk, T. Budzik, M. Grabiec, J.A. Jania, M. Kondracka, M. Laska, L. Malarzewski, and L. Stachnik. A decade of glaciological and meteorological observations in the Arctic (Werenskioldbreen, svalbard). *Earth System Science Data*, 14:2487–2500, 6 2022.
- [7] A. Nowak and A. Hodson. Hydrological response of a High-Arctic catchment to changing climate over the past 35 years: a case study of Bayelva watershed, Svalbard. *Polar Research*, 1:1–16, 2013.
- [8] N. G. Midgley, T. N. Tonkin, D. J. Graham, and S. J. Cook. Evolution of high-arctic glacial landforms during deglaciation. *Geomorphology*, 311:63–75, 2018.
- [9] T.R. Chudley, P. Christoffersen, S.H. Doyle, M. Bougamont, C.M. Schoonman, B. Hubbard, and M.R. James. Supraglacial lake drainage at a fast-flowing greenlandic outlet glacier. *Proceedings of the National Academy of Sciences of the United States of America*, 116:25468–25477, 2019.
- [10] M.W. Ewertowski, A.M. Tomczyk, D.J.A. Evans, D.H. Roberts, and W. Ewertowski. Operational framework for rapid, very-high resolution mapping of glacial geomorphology using low-cost unmanned aerial vehicles and structure-from-motion approach. *Remote Sensing*, 11, 1 2019.
- [11] I. Sobota. *Atlas of Changes in the Glaciers of Kaffiøyra:(Svalbard, the Arctic)*, chapter Glaciers of Kaffiøyra, page 82. Nicolaus Copernicus University Press, 2021.
- [12] D. Harden, P. Barnes, and E. Reimnitz. Distribution and character of naleds in northeastern Alaska. *Arctic*, pages 28–40, 1977.
- [13] E. Bukowska-Jania and J. Szafraniec. Distribution and morphometric characteristics of icing fields in Svalbard. *Polar Research*, 24:41–53, 2005.

- [14] E. Bukowska-Jania. The role of glacier system in migration of calcium carbonate on Svalbard. *Polish Polar Research*, 28:137–155, 2007.
- [15] G. Schwamborn, J. Heinzl, and L. Schirrmeister. Internal characteristics of ice-marginal sediments deduced from georadar profiling and sediment properties (Brøgger Peninsula, Svalbard). *Geomorphology*, 95:74–83, 3 2008.
- [16] O. Sass and M. Krautblatter. Debris flow-dominated and rockfall-dominated talus slopes: Genetic models derived from GPR measurements. *Geomorphology*, 86:176–192, 4 2007.
- [17] A. Chesnokova, M. Baraër, and É. Bouchard. Proglacial icings as records of winter hydrological processes. *The Cryosphere*, 14(11):4145–4164, 2020.
- [18] I. Sobota, P. Weckwerth, and T. Grajewski. Rain-on-snow (ROS) events and their relations to snowpack and ice layer changes on small glaciers in Svalbard, the high Arctic. *Journal of Hydrology*, 590:125279, 2020.
- [19] P. Weckwerth and I. Sobota. Morphology and surficial sediments of the Waldemar River confined outwash fan. *Bulletin of Geography, Physical Geography series*, 13:61–70, 2017.
- [20] K. Lamsters, Jurijs Ješkins, Ireneusz Sobota, Jānis Karušs, and Pēteris Džeriņš. Surface characteristics, elevation change, and velocity of high-arctic valley glacier from repeated high-resolution UAV photogrammetry. *Remote Sensing*, 14:1029, 2022.
- [21] I. Sobota. Icings and their role as an important element of the cryosphere in High Arctic glacier forefields. *Bulletin of Geography, Physical Geography series*, 10:81–93, 2016.
- [22] T. Głowacki and D. Kasza. Assessment of morphology changes of the end moraine of the Werenskiöld glacier (SW Spitsbergen) using active and passive remote sensing techniques. *Remote Sensing*, 13(11):2134, 2021.
- [23] J. Karušs, K. Lamsters, I. Sobota, J. Ješkins, P. Džeriņš, and A. Hodson. Drainage system and thermal structure of a High Arctic polythermal glacier: Waldemarbreen, Western Svalbard. *Journal of Glaciology*, 68:591–604, 6 2022.
- [24] E. Bukowska-Jania and J. Szafraniec. Distribution and morphometric characteristics of icing fields in Svalbard. *Polar Research*, 24(1-2):41–53, 2005.
- [25] J. Åkerman. Periglacial forms of Svalbard: a review. *Periglacial Processes and Landforms in Britain and Ireland. Cambridge University Press, Cambridge*, pages 9–25, 1987.

- [26] G. Rachlewicz. Paraglacial modifications of glacial sediments over millennial to decadal time-scales in the High Arctic (Billefjorden, Central Spitsbergen, Svalbard). *Quaestiones Geographicae*, 29:59–67, 2010.
- [27] É. Bernard, J.-M. Friedt, F. Tolle, C. Marlin, and M. Griselin. Using a small cots UAV to quantify moraine dynamics induced by climate shift in Arctic environments. *International Journal of Remote Sensing*, 0:1–15, 2016.
- [28] S. Ai, X. Ding, J. An, G. Lin, Z. Wang, and M. Yan. Discovery of the fastest ice flow along the central flow line of Austre Lovénbreen, a poly-thermal valley glacier in Svalbard. *Remote Sensing*, 11, 2019.
- [29] J.K. Hart, K. Martinez, P.J. Basford, A.I. Clayton, G.M. Bragg, T. Ward, and D.S. Young. Surface melt-driven seasonal behaviour (englacial and subglacial) from a soft-bedded temperate glacier recorded by in situ wireless probes. *Earth Surface Processes and Landforms*, 44:1769–1782, 7 2019.
- [30] T. N. Tonkin, N. G. Midgley, S. J. Cook, and D. J. Graham. Ice-cored moraine degradation mapped and quantified using an unmanned aerial vehicle: A case study from a polythermal glacier in Svalbard. *Geomorphology*, 258:1–10, 4 2016.
- [31] C.L. Fyffe, A.S. Woodget, M.P. Kirkbride, P. Deline, M.J. Westoby, and B.W. Brock. Processes at the margins of supraglacial debris cover: Quantifying dirty ice ablation and debris redistribution. *Earth Surface Processes and Landforms*, 45:2272–2290, 8 2020.
- [32] C. Marlin, F. Tolle, M. Griselin, E. Bernard, A. Saintenoy, M. Quenet, and J.-M. Friedt. Change in geometry of a high arctic glacier from 1948 to 2013 (Austre Lovénbreen, Svalbard). *Geografiska Annaler: Series A, Physical Geography*, pages 1–24, 2 2017. doi: 10.1080/04353676.2017.1285203.
- [33] J.-M. Friedt, F. Tolle, É. Bernard, M. Griselin, D. Laffly, and C. Marlin. Assessing the relevance of digital elevation models to evaluate glacier mass balance: application to Austre Lovénbreen (Spitsbergen, 79°N). *Polar Record*, 48:2–10, 11 2011.
- [34] M. Eckerstorfer and H.H. Christiansen. The “High Arctic Maritime Snow Climate” in Central Svalbard. *Arctic, Antarctic, and Alpine Research*, 43:11–21, 2 2011.
- [35] C.M. Debeer and J.W. Pomeroy. Modelling snow melt and snowcover depletion in a small alpine cirque, Canadian Rocky Mountains. *Hydrological Processes*, 2599:2584–2599, 2009.
- [36] J.A. VanLooy and G.S. Vandeberg. Late summer glacial meltwater contributions to Bull Lake Creek stream flow and water quality, Wind River Range, Wyoming, USA. *Physical Geography*, 40:461–480, 2019.

- [37] S. Lukas, L.I. Nicholson, F.H. Ross, and O. Humlum. Formation, meltout processes and landscape alteration of High-Arctic ice-cored moraines — examples from Nordenskiöld Land, Central Spitsbergen. *Polar Geography*, 29:157–187, 2005.
- [38] A. Prokop and H. Panholzer. Assessing the capability of terrestrial laser scanning for monitoring slow moving landslides. *Natural Hazards and Earth System Sciences*, 9(6):1921–1928, 2009.
- [39] RIEGL Laser Measurement Systems. Riegl laser measurement systems: Data sheet rieg1 vz-6000 – 3d ultra long range terrestrial laserscanner with online waveform processing, 2018.
- [40] RIEGL Laser Measurement Systems. Riscan pro – version 2.1.1, 2015.
- [41] Norwegian Polar Institute. Terrengmodell svalbard (s0 terrengmodell) data set, 2014.
- [42] Cloudcompare (version 2.12), 2023. <http://www.cloudcompare.org/>.
- [43] Steven A Arcone, Daniel E Lawson, and Allan J Delaney. Short-pulse radar wavelet recovery and resolution of dielectric contrasts within englacial and basal ice of matanuska glacier, alaska, usa. *Journal of Glaciology*, 41(137):68–86, 1995.
- [44] AP Annan. Ground penetrating radar applications, principles, procedures. *Mississauga, Canada: Sensors and Software*, 2004.
- [45] O. Makarieva, A. Shikhov, N. Nesterova, and A. Ostashov. Historical and recent aufeis in the Indigirka River basin (Russia). *Earth System Science Data*, 11(1):409–420, 2019.
- [46] K. Yoshikawa, L.D Hinzman D, and D.L. Kane. Spring and aufeis (icing) hydrology in Brooks Range, Alaska. *Journal of Geophysical Research: Biogeosciences*, 112(G4), 2007.
- [47] O. Makarieva, N. Nesterova, A. Shikhov, A. Zemlianskova, D. Luo, A. Ostashov, and V. Alexeev. Giant aufeis—unknown glaciation in North-Eastern Eurasia according to Landsat images 2013–2019. *Remote Sensing*, 14(17):4248, 2022.
- [48] T. Ensom, O. Makarieva, P. Morse, D. Kane, V. Alekseev, and P. Marsh. The distribution and dynamics of aufeis in permafrost regions. *Permafrost and Periglacial Processes*, 31(3):383–395, 2020.
- [49] E. Wohl and J.E. Scamardo. Aufeis as a major forcing mechanism for channel avulsion and implications of warming climate. *Geophysical Research Letters*, 49(20):e2022GL100246, 2022.
- [50] D.L. Kane. Physical mechanics of aufeis growth. *Canadian Journal of Civil Engineering*, 8(2):186–195, 1981.

[51] N.S. Arnold, W.G Rees, B.J. Devereux, and G.S Amable. Evaluating the potential of high-resolution airborne lidar data in glaciology. *International Journal of Remote Sensing*, 27(6):1233–1251, 2006.

A Channel carving observation from LiDAR DEM differences

In order to compare the hydrographic network evolution over a longer period, we expanded the analysis duration by using an aerial LiDAR map acquired in 2005 [51] over Midtre and Austre Lovénbreen, with a 2 m regular grid horizontal resolution. This dataset, collected over 10 years before our own ground-based LiDAR measurements, provides a baseline on the moraine topography as the glacier was still covering areas now exposed to erosion.

DEMs obtained by successive LiDAR measurements are used for modeling the water flow in the hydrographic networks (Fig. 17), with the complete shift in stream location between 2005 and 2021. As discussed in the main text, field observations date this shift to the year 2015. On Fig. 17 (right), LiDAR DoD profiles 1 to 3 are numbered incrementally according to the stream flow from the south to the north. The current channel shown in dashed light blue line on Fig. 17 (A) runs along an area that was observed as flat in 2005, emphasizing how it does not follow a paleo-channel but carved a new channel in the fine-grained sediment.

B Latest developments

Opportunistic aerial images of Austre Lovénbreen were collected on each flight from Longyearbyen to Ny-Ålesund: the autumn pictures highlight the hydrographic network and provide an overview of flow patterns. As shown on Fig. 18, the river network has remained unchanged since 2017, with stabilized riverbeds and icings no longer able to control an oscillation between outlet canyons due to the lower elevation of the newly carved riverbed.

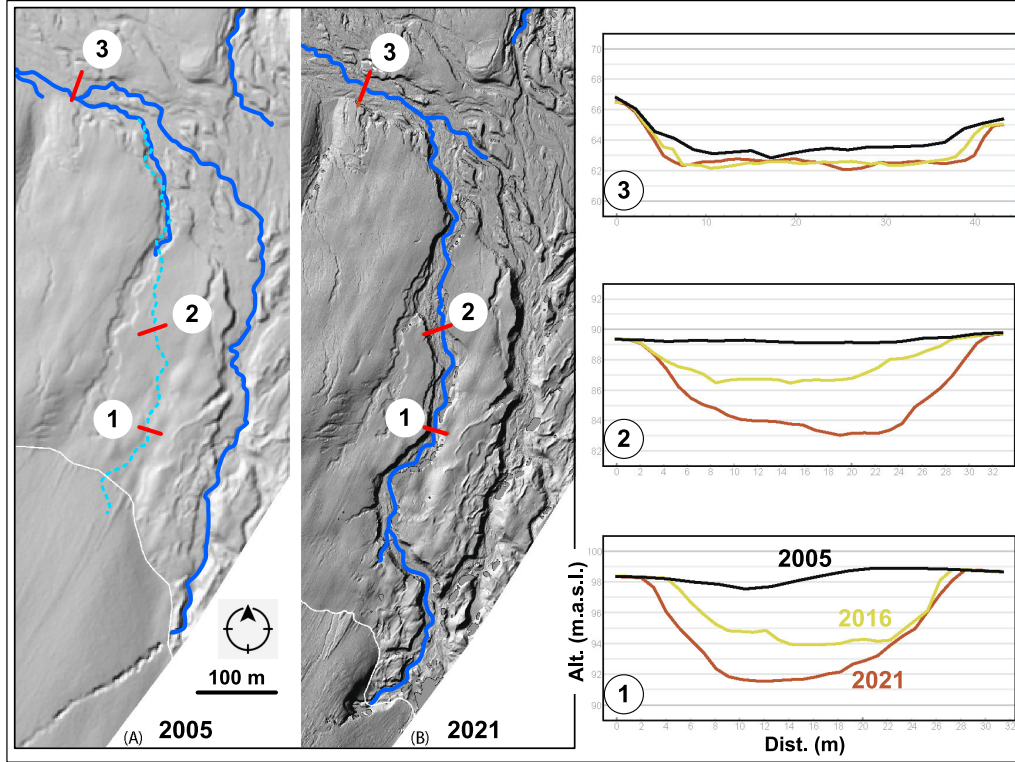


Figure 17: Glacier front and main river outlet of the glacier basin shown as a hill-shaded rendering of the 2005 DEM (A, left) at 2 m resolution and the 2021 DEM (B, middle) at 1 m resolution. The glacier front is outlined in white at the South-West corner of each scene. Outlet stream delineations are outlined in solid blue lines as derived from each DEM respectively, and light dashed blue line on Fig (A, left) is a copy of the current channel (B) on the DEM of 2005 highlighting how flat the area was prior to being carved by the new channel. Right: cross sections along paths indicated in red on (A) and (B) for the three DEM collected in 2005, 2016 and 2021.

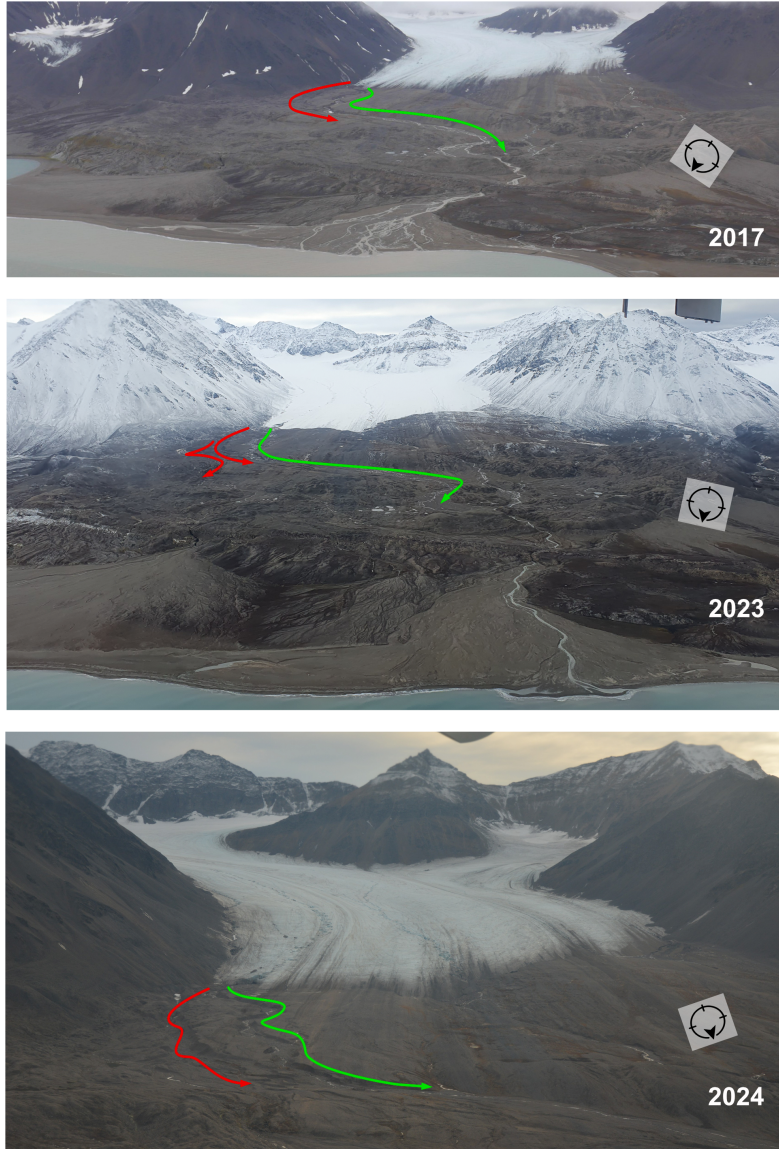


Figure 18: Opportunistic aerial images of Austre Lovénbreen collected between 2017 and 2024 highlighting how the water streams always follow the same channel since the deep canyon was carved in the easy-to-move sediments exposed by the retreating glacier, ending the oscillation between outlets illustrated in Fig. 13. The arrows guide the eye towards active water flows (green) and inactive channels (red) with the direction of flow determined by the arrow head.