Submarine Landforms in a Surge-Type Tidewater Glacier Regime, Engelskbukta, Svalbard

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Abstract

Though surge-type glaciers make up a small percentage of the world's outlet glaciers, they have the potential to further destabilize the larger ice caps and ice sheets that feed them during a surge. Currently, mechanics that control the duration and ice flux from a surge remain poorly understood. Here, we examine submarine glacial landforms in bathymetric data from Engelskbukta, a bay sculpted by the advance and retreat of Comfortlessbreen, a surge-type glacier in Svalbard, a high Arctic archipelago where surge-type glaciers are especially prevalent. These landforms and their spatial and temporal relationships, and mass balance from the end of the last glacial maximum, known as the Late Weichselian in Northern Europe, to the present. Beyond the landforms representing modern proglacial sedimentation and active iceberg scouring, distinct assemblages of transverse and parallel crosscutting moraines denote past glacier termini and flow direction. By comparing their positions with dated deposits on land, these assemblages help establish the chronology of Comfortlessbreen's surging and retreat. Additional deformations on the seafloor showcase subterranean Engelskbukta as the site of active thermogenic gas seeps. We discuss the limitations of local sedimentation and data resolution on the use of bathymetric datasets to interpret the past behavior of surging tidewater glaciers.

1. Introduction

In the Arctic, many marine-terminating, or tidewater, glaciers are classified as surge-type systems, exhibiting normal flow conditions in a quiescent phase lasting years or decades. This period of inactivity is later followed by a dramatic speedup in ice flow and advance of the terminus, then a net retreat due to mass loss from iceberg calving. Numerous studies have attempted to identify external factors that control a glacier's surge status and cycle, suggesting that mass balance conditions, local climate, and the slope and sedimentary composition of the glacier bed may help quantify the frequency and duration of past surges. [*Jiskoot et al.*, 2000; *Ottesen and Dowdeswell*, 2006]

The landforms produced on the seafloor by the presence and flow of grounded tidewater glaciers remain remarkably well-preserved. This detailed seafloor record is due to the lack of subaerial erosion processes and low sedimentation rates along much of the glacial fjord. As glaciers advance, they deform the underlying sediments, forming suites of lineations at the terminus and bed proportional in size and number to the size and speed of the glacier.

Here, we examine the structural characteristics in bathymetric data from Engelskbukta, a glacially-scoured bay in West Spitsbergen, Svalbard (Figure 1) for evidence of historical glacier dynamics. We identify and interpret suites of landforms in the bathymetry of the fjord that illustrate the past presence and flow of the Comfortlessbreen tidewater glacier. These landforms offer evidence of Comfortlessbreen's past and present surge dynamics as a response to both local and global environmental change.

2. Setting

Engelskbukta is a bay bordered on the north by the Brøggerhalvøya peninsula, on the southeast by Comfortlessbreen, a large tidewater glacier, and on the east by Uversøyra, a delta formed by the melting and outwash of the land-anchored Uversbreen glacier (78° 49' N -78° 55' N, 11°E-12°E).

Estimates of the percentage of surge-type glaciers in Svalbard range from 13-90%. [*Błaszczyk et al.*, 2009; *Sund et al.*, 2009] Detailed observations of terminus positions and crevasse propagation in Comfortlessbreen beginning in 2001 confirmed its status as a surge-type glacier, and established that by 2006, it had entered active surging with an average velocity of 2 m d^{-1} [*Sund and Eiken*, 2010], compared to a quiescent-phase velocity of 55 m yr^{-1}. [*Błaszczyk et al.*, 2009; *Schneevoigt et al.*, 2011]

Based on stratigraphy and radiocarbon dating from the adjacent raised beaches on Brøggerhalvøya, Comfortlessbreen is thought to have retreated from its Late Weichselian maximum extent between 9.5-10.0 kYa. [*Forman*, 1989] Because of this relatively early retreat from the fjord, swath imagery offers a chance to examine the morphology of sediment-blanketed landforms [*Ottesen and Dowdeswell*, 2009] and to compare these landforms to those produced by much more recent glacial retreats in Svalbard. [*Ottesen and Dowdeswell*, 2006; *Ottesen et al.*, 2008]

3. Methods

The Norwegian Mapping Authority (Statens Kartverk) conducts multibeam bathymetric surveys around Norway and Svalbard and provided this dataset to the University Centre on Svalbard (UNIS) for research purposes. The Engelskbukta dataset (Figure 2) was acquired from 2004-2008 aboard the *R/V* Hydrograf using a Kongsberg EM710 multibeam echosounder [*Norwegian Hydrographic Service*, 2010] and spans 3-30 km from the Comfortlessbreen terminus past the Brøggerhalvøya peninsula, extending north and south into Forlandsundet, a narrow sound between Spitsbergen and the island Prins Karls Forland. The data was gridded at a 5-meter resolution, post-processed and corrected for tides, ship parameters, and noise, and was visualized using the CARIS HIPS and SIPS and BathyDataBASE packages.

4. Results

Here, we interpret six unique morphologies present in the seafloor record in Engelskbukta. These bedforms show evidence of modern deltaic sedimentation, transverse and parallel subglacial lineations that represent the direction and timing of past glacier flow, thermogenic pockmarks, iceberg keel scars, and slides from mass wasting on the sides of the fjord. These bedforms confirm the accuracy and utility of the submarine landsystem models detailed by Ottesen and Dowdeswell. [2006, 2009]

4.1. Modern Deltaic Deposits

Features closest to the glacier terminus indicate a lobe of significant glaciomarine sediment deposition overlain with small undulations that could represent pulsed sedimentation from glacial outwash or local gravity flows within the lobe. The location of the main sediment lobe matches the deltaic sediment plume visible in aerial imagery. (Figure 3)The spacing and relief of these undulations may represent pulsing from glacial outwash streams, cyclic deposition by the action of local tides on the fjord, or both. Alternatively, small scale undulations in the sediment lobe could be formed by local slope processes. The undulations have differing orientations, but follow the large-scale slope of the lobe.

Submarine channels at this margin match up well with the positions of the major meltwater rivers at the Comfortlessbreen-Uversbreen delta system. The large-scale bathymetry and channels in the main sediment lobe indicate formation by a grounding-line fan at a past glacier terminus by entrained subglacial sediment. [*Boulton*, 1986; *Powell*, 1990] The sediment lobe is at a depth of 40-70 m, confirming that it could not have formed on land at any time after the Late Weichselian glacial maximum. [*Forman et al.*, 1987]

4.2. Transverse Ridges

Large transverse ridges are observed throughout the fjord (Figure 4), ranging from 5-20 m in height and 100-500 m in length. Smaller ridges within 4 km of the glacier terminus have 2m heights and spacing of approximately 100 m between them. The geometry of these ridges suggests annual push moraines, similar to those found at other tidewater margins in Svalbard. [*Boulton*, 1986; *Ottesen and Dowdeswell*, 2009] However, their presence only on the sides of the fjord and not in the central bed highlights the smoothed, thickly-sedimented nature of the Engelskbukta system.

Baeten et al. [2010] observed similar ridges overlaying the parallel lineations, and suggested that if the ridges are thin, undulating, and discontinuous, then they may be crevasse squeeze ridges created during a surge.

Finally, a large ridge at the mouth of the fjord is interpreted as the main glacial sill. (Figure 5) The sill, with a relief of 30 m from the adjacent fjord floor and over 60 m above the Forlandsundet basin, marks the seafloor impression of Comfortlessbreen's glacial maximum. This extent closely matches the inferred Late Weichselian terminus position of the Comfortlessbreen glacier from isotope dating on Brøggerhalvøya by Forman. [1989]

4.3. Parallel Lineations

Parallel mega-scale glacial lineations approximately 5 m high and 50-150 m wide are observed and indicate the direction of past glacier flow. [*Baeten et al.*, 2010; *Dowdeswell et al.*, 2008, 2010; *Ottesen and Dowdeswell*, 2006, 2009; *Ottesen et al.*, 2005, 2007] In Engelskbukta, these lineations run parallel to the fjord axis, before curving to a northwest orientation hugging the Brøggerhalvøya peninsula. Like the transverse moraine ridges, these parallel lineations end at the shallow sill at the mouth of the bay. Near a large thrust moraine, some of these lineations may represent the remnants of an underwater grounding-line fan.

Many of the parallel lineations are overlaid by transverse lineations, signifying that the parallel lineations were formed by glacial advance, with the cross-cutting transverse moraines ridges building as push moraines produced by surges during glacial retreat. [*Ottesen et al.*, 2008]

4.4. Pockmarks

Pockmarks are widely distributed in two main regions in this dataset. The largest region stretches 8 km from the sill into the fjord, spanning the entire width of the fjord. Another field is located in Forlandsundet north of Engelskbukta. (Figure 6)

Pockmarks range in depth from 4-8 meters, averaging 5 meters in Engelskbukta. (Fig. 6) Their raised rims, increasing dip with depth, and tendency to appear in chains suggest processes identical to the fjord floor pockmarks observed by Forwick et al. [2009] The pockmarks are formed from thermogenic gas seeping out of the sediment layers. However, the exact chemistry, quantity, and distribution of this thermogenic gas are areas of active research.

4.5. Iceberg Scars and Slides

Numerous iceberg keel scars are observed past the mouth of Engelskbukta in the adjacent Forlandsundet. (Figure 7) These scars are caused by the submerged keels of icebergs calved from nearby glaciers; when the icebergs drift into an area of shallower bathymetry due to local ocean currents, the keels cause linear indentations in the bed with a depth proportional to the overlying vertical force by the ice mass and a length dependent on the extent of the shallow topography.

In Forlandsundet, these scars are approximately 1-2 meters deep, 10-20 meters wide, and can range from point depressions to lineations exceeding 1 kilometer, depending on the bathymetry. The scars are present only in areas shallower than 40 m, consistent with similar observations in neighboring Kongsfjorden. [*Dowdeswell and Forsberg*, 1992] Additionally, the linear scars maintain a primarily north-south orientation, consistent with the orientation of ocean circulation in the narrow sound.

5. Discussion

Throughout Engelskbukta, the submarine glacial landforms have shallower relief slopes than landforms built by the same surging processes in nearby fjords. Because of Comfortlessbreen's early retreat from the fjord, [*Forman*, 1989] into a hybrid tidewater/land-based ice-contact delta terminus, the sediment layer in Engelskbukta is significantly thicker than in other locations recently imaged after glacial retreat in the last century. Elverhøi et al. [1983] bracketed sediment layer thicknesses in several fjords in West Spitsbergen at 5-20 m from sub-bottom profiler data. At the neighboring Kronebreen-Kongsvegen tidewater glacier complex, they observed average sedimentation rates of 0.1-1.0 mm yr^{1} in the outer fjord and up to 50-100 mm yr^{-1} within 10 km of the calving glacier terminus. Recent studies at the Kronebreen terminus have shown spatially variable sedimentation rates ranging from 0.3-2.0 m yr^{1}, with mid-fjord settling measured at 60-90 mm yr^{-1}. [*Kehrl et al.*, 2011; *Trusel et al.*, 2010] Though the combined Comfortlessbreen-Uversbreen system's surface velocity and calving mass flux are a full order of magnitude less than those found at the Kronebreen-Kongsvegen terminus, [*Błaszczyk et al.*, 2009; *Kaab et al.*, 2005] a proportionally lower sediment flux into Engelskbukta is able to smooth features tens of meters tall over century timescales.

A 4 km region in the middle of the fjord lacks consistent, well-defined orientations for ridge features, with much of the small-scale bathymetry near the edges composed of rough, hummocky mounds of sediments. This terrain is described in Van Mijenfjorden, another surge-typeWest Spitsbergen fjord, by Kristensen et al. [2009] as subglacial sediment squeezed upward into basal crevasses [*Boulton et al.*, 1996] or thrust up into the terminus ice by a surge then re-deposited during a retreat. [*Hambrey et al.*, 1997]

Data resolution also plays a role in determining whether smaller landforms are visible. Other studies interpreting Svalbard fjord bathymetry have used data gridded at 1-2 meter resolution. Eskers, formed by subglacial meltwater conduits and subsequent infilling by subglacial sediments, and crevasse-fill ridges, formed by sediments infilling subglacial transverse crevasses, are present at these smaller scales. [*Ottesen and Dowdeswell*, 2009; *Ottesen et al.*, 2008] Analyses of higher-resolution datasets are able to better resolve feature slopes, enabling discrimination of these smaller features from annual push moraines and other parallel glacial lineations.

6. Conclusions

Several large transverse ridges appear throughout the fjord, which may indicate the grounding line morainal banks deposited during active surge phases and as the glacier gradually retreated. Dates from corresponding moraine deposits on land can help constrain the surge frequency and its variability.

Many of the landforms in the fjord are smoother and have shallower relief than can be observed in other Svalbard fjords with large, active, surge-type glaciers. The added sediment deposition from the Uversøyra delta may account for this.

Submarine landform assemblages interpreted from multibeam surveys are by themselves insufficient evidence to definitively determine whether or not a glacier is surge-type. [*Bennett et al.*, 1999; *Ottesen and Dowdeswell*, 2006] Studies investigating surge status and dynamics must combine surface time-series observations of glacier flow with this submarine data to establish a more complete and detailed glacier chronology, and to link this chronology with the glacier's internal mechanics and surrounding climate. By correlating the surge landforms with reconstructions of past mass balance and climate forcing, we can begin to predict how future conditions will influence these glaciers, the ice flux from their inland ice sheets, and their contribution to sea level rise.

Acknowledgements

The authors thank the Norwegian Hydrographic Service for providing the bathymetric data in this research. UNIS, the Norsk Polarinstitutt (Norwegian Polar Institute), and the Kings Bay Company provided invaluable logistical support. The undergraduate fieldwork in Svalbard in Summer 2011 that served as a nucleus for this work was funded by National Science Foundation grant OPP-0649006.

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Figures

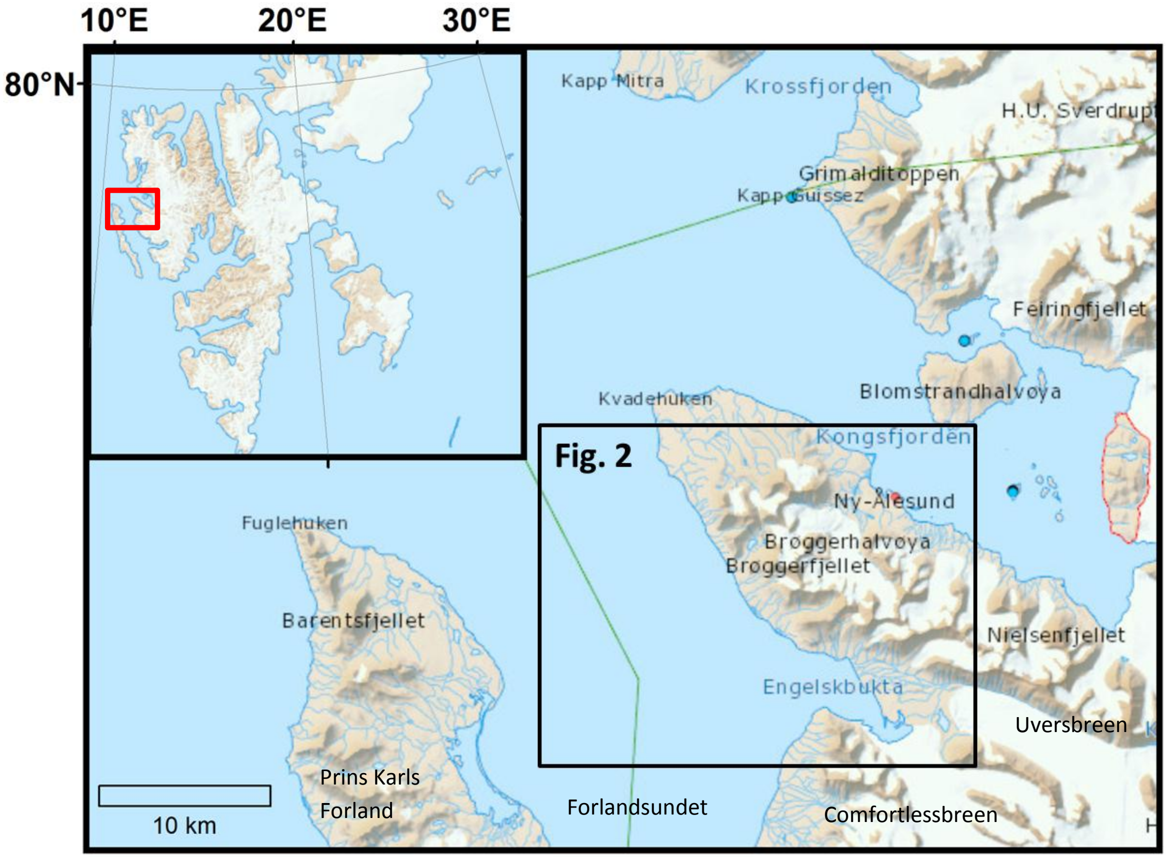

Figure 1. An overview of Engelskbukta in Svalbard (inset) and surrounding features, including the Brøggerhalvøya peninsula, the Comfortlessbreen and Uversbreen glaciers, and neighboring Forlandsundet and Prins Karls Forland to the west.

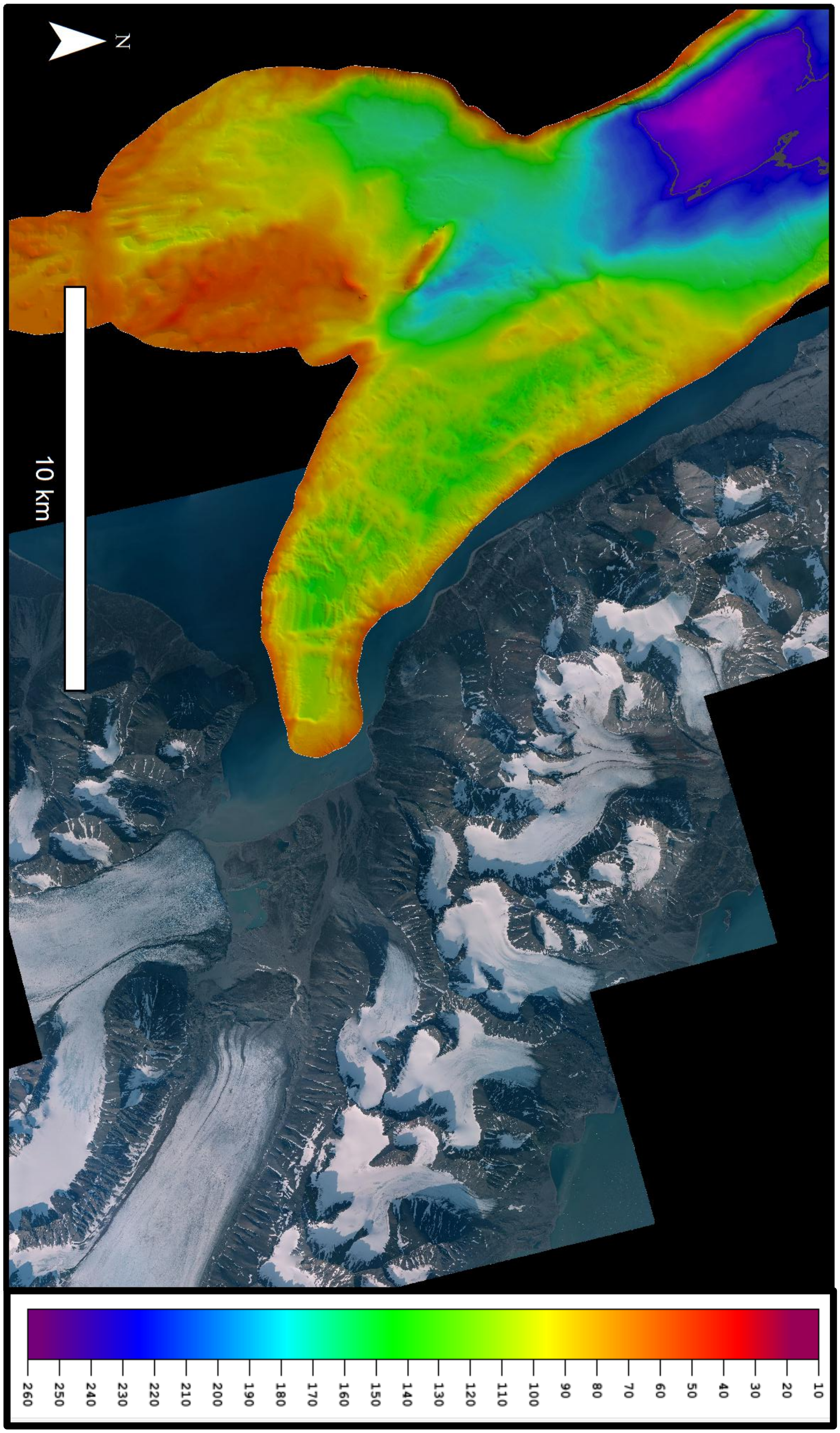

Figure 2.View of the bathymetric data in Engelskbukta, overlaid on an aerial photomosaic with imagery taken in 2009 by the Norsk Polarinstitutt.

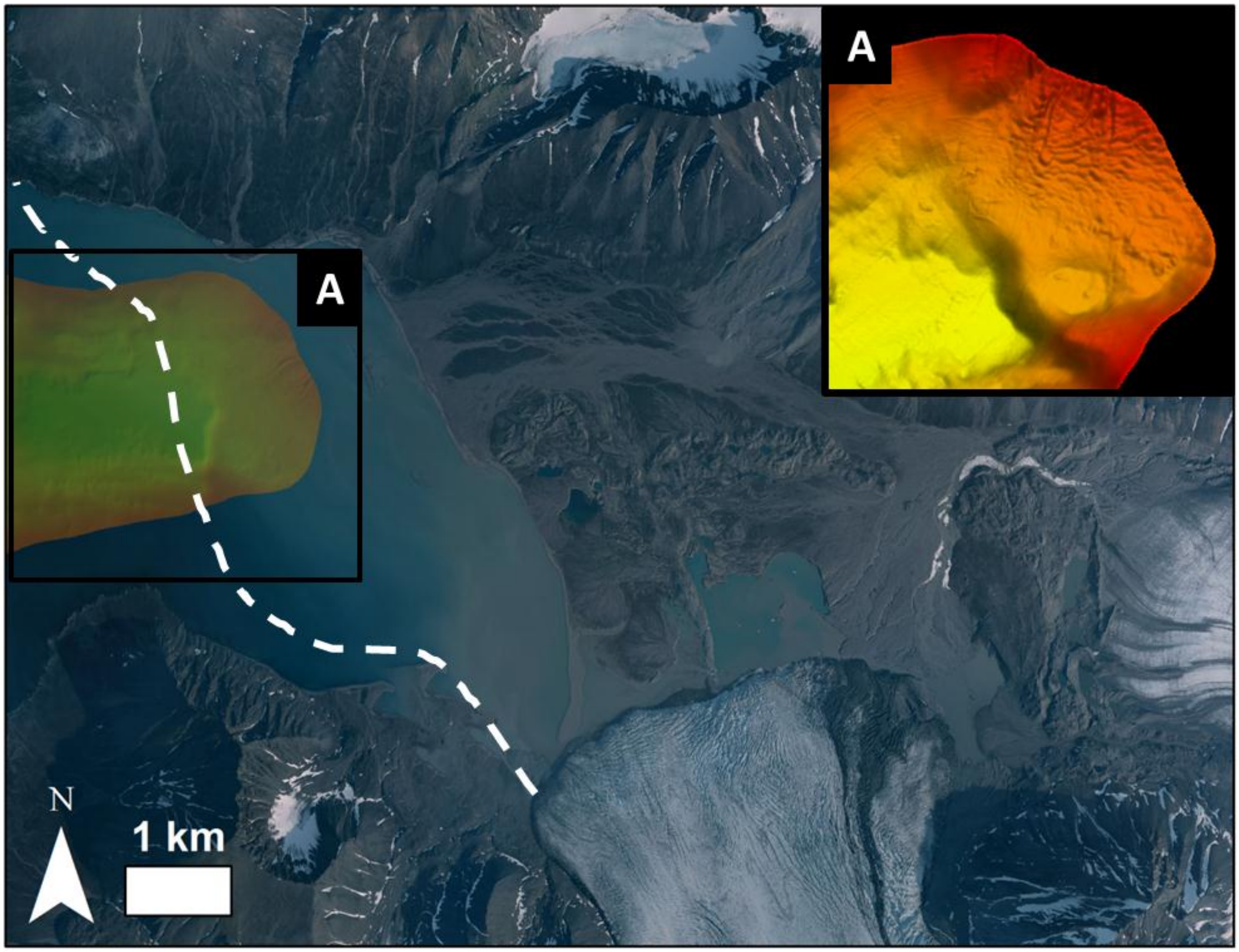

Figure 3. Aerial photomosaic from the Norsk Polarinstitutt detailing the combined Comfortlessbreen-Uversbreen glacial delta and the shallow extent of the bathymetric data (inset A). The white dotted line marks the visible surface extent of the deltaic sediment plume, which matches the extent of the initial sediment lobe in the bathymetry. Inset A details the bathymetry of the sediment lobe (6x vertical exaggeration) showing channels and undulations.

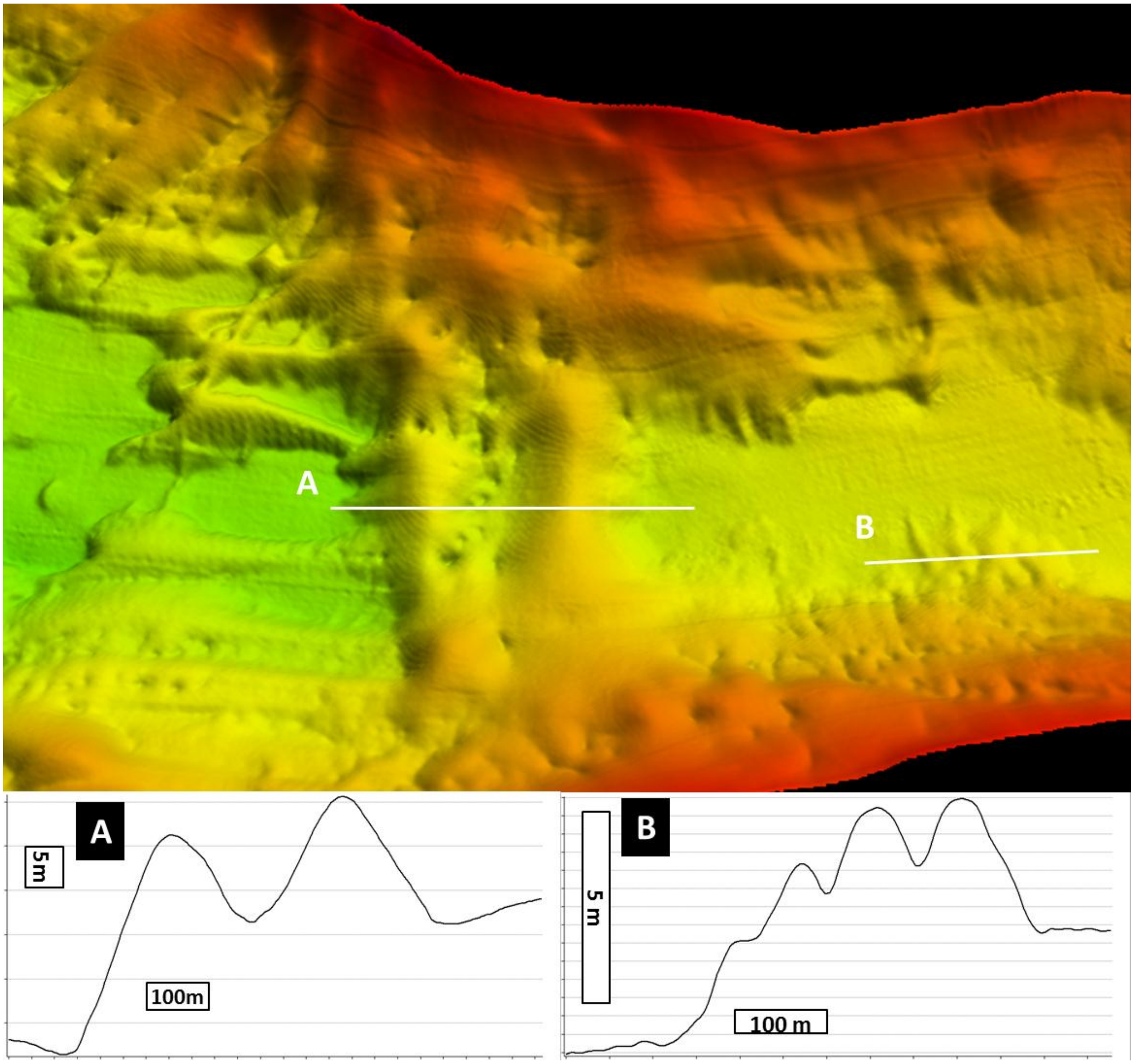

Figure 4. Detail of the area between the sediment lobe and the mid fjord (6x vertical exaggeration), with profiles over two sets of transverse moraine ridges. Profile A is interpreted as a set of larger thrust moraines, possibly produced during a surge, with relief of 10-15 m followed by a steep topographic ledge. Profile B, interpreted as remnants of annual retreat moraines with 1-2 m of residual surface relief above their heavily-sedimented bed.

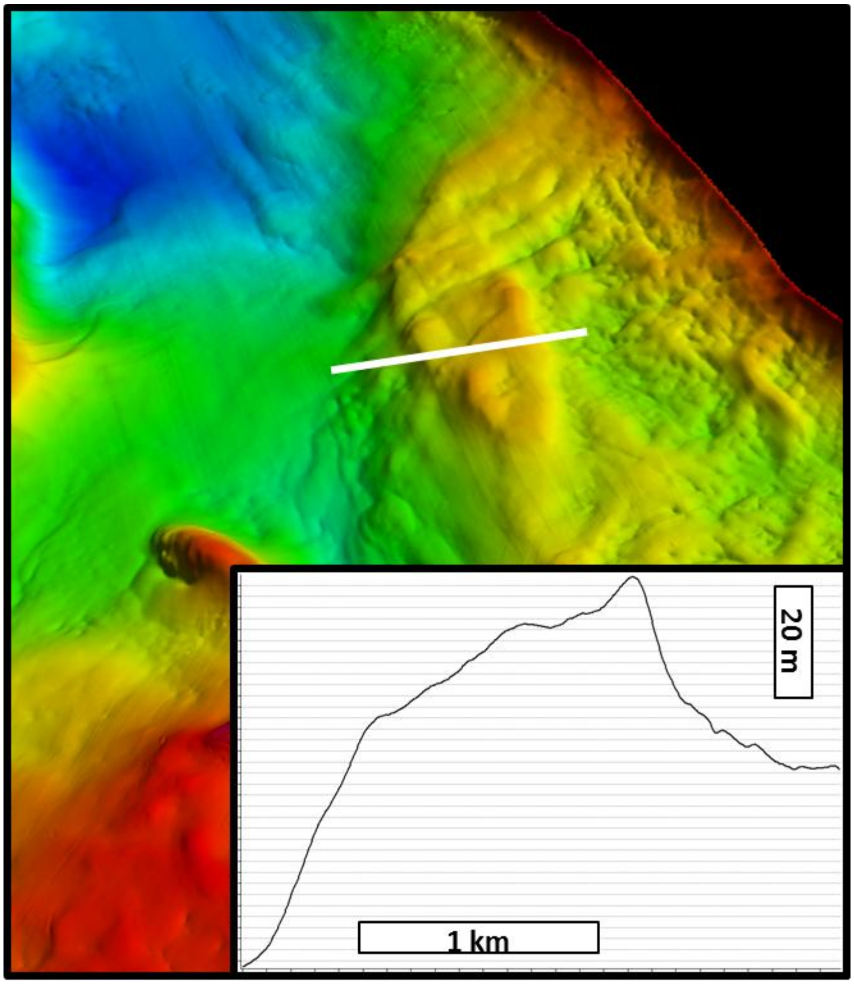

Figure 5. The sill feature located at the end of the fjord (6x vertical exaggeration). The profile (inset) indicates 20-30 m of surface relief from the fjord with over 1 km of sediment built at the paleo- Comfortlessbreen grounding line. The large volume of this sill indicates that the grounding line remained stable throughout the Late Weichselian, with the building sill insulating the glacier terminus from oceanic melting.

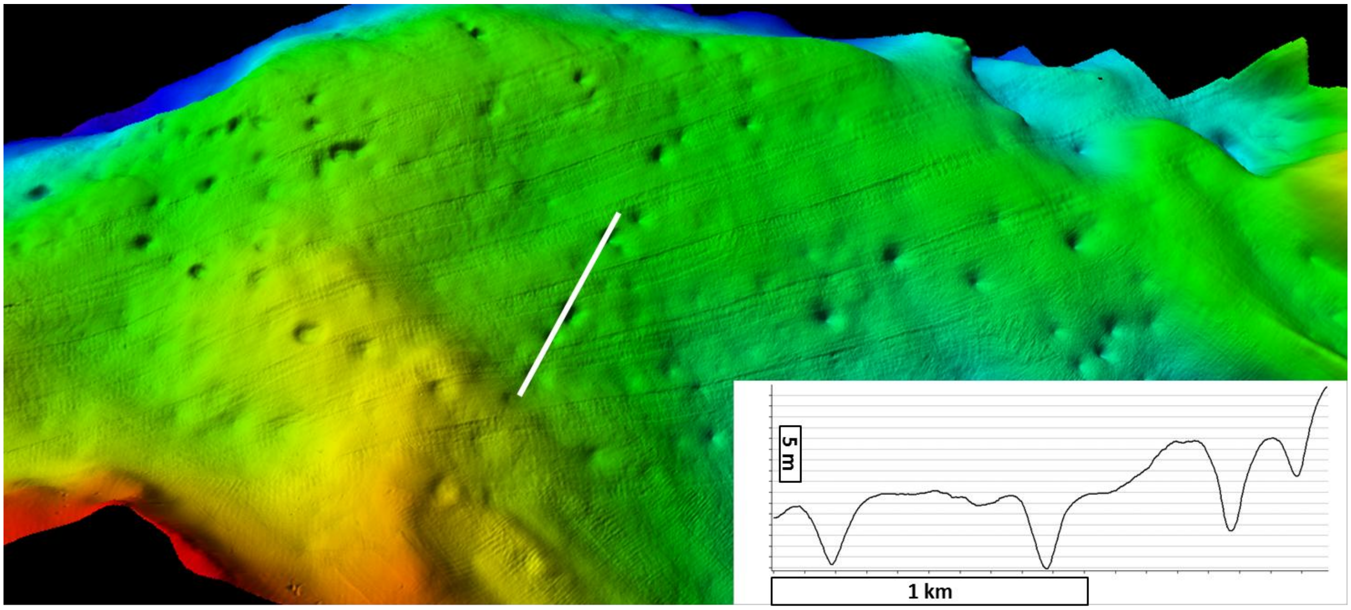

Figure 6. Gas pockmarks in Forlandsundet north of Engelskbukta (6x vertical exaggeration). The pockmarks tend to cluster or chain, sometimes forming composite pockmarks, detailed in Forwick et al. [2009]The profile (inset) details the bathymetry of the pockmarks.

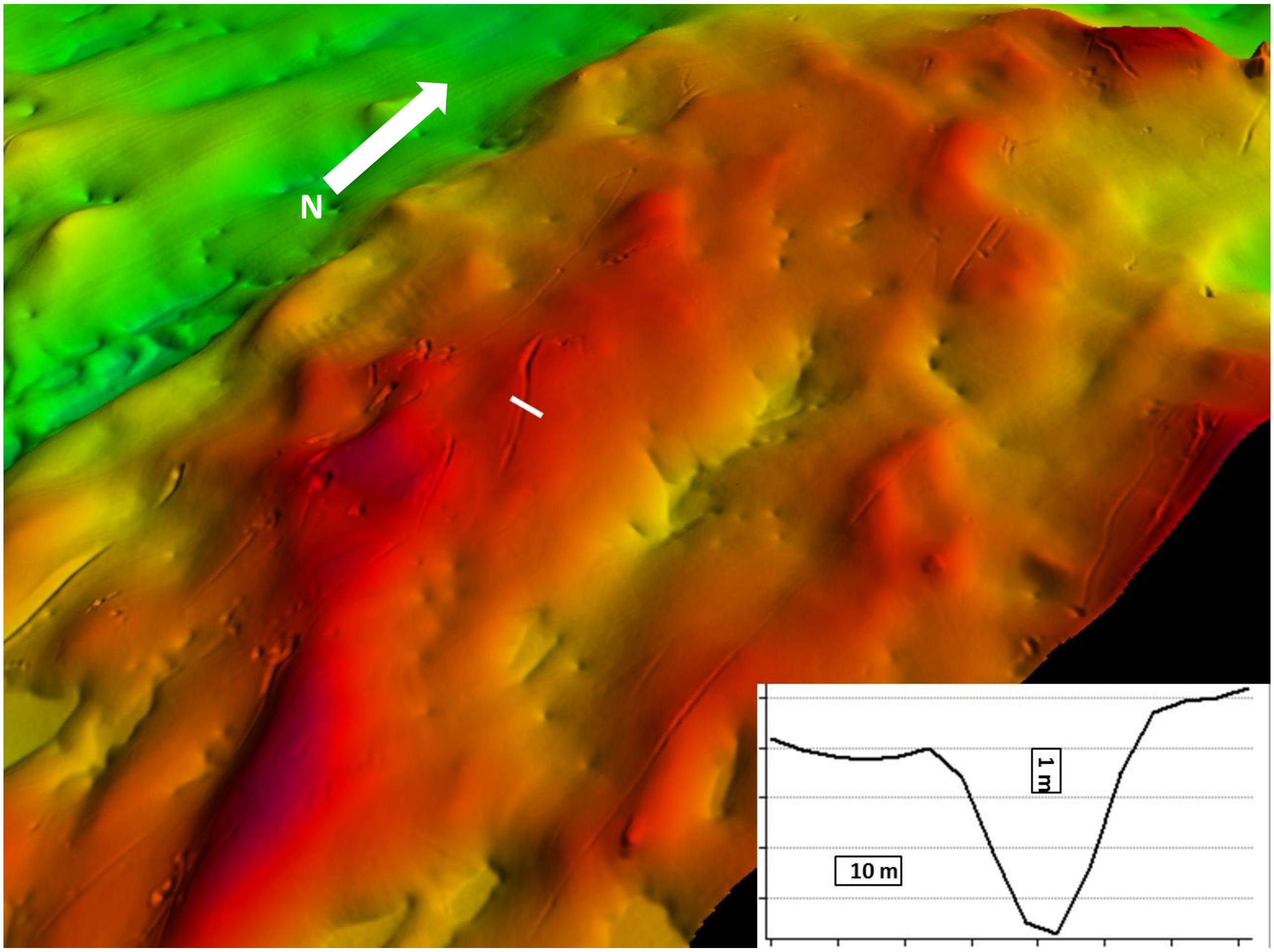

Figure 7. Iceberg keel scars in Forlandsundet south of Engelskbukta, with 10x vertical exaggeration. A profile (inset) shows the magnitude of the surface impression.The scars are oriented north-south along the sound.