# Submarine geomorphology at the front of the retreating Hansbreen tidewater glacier, Hornsund fjord, southwest Spitsbergen

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**ABSTRACT**
A 1:10,000 scale bathymetric map as well as 1:20,000 scale backscattering and geomorphological maps of two bays Isbjørnhamna and Hansbukta in the Hornsund fjord (Spitsbergen) present the submarine relief that was primarily formed during and after the retreat of the Hansbreen tidewater glacier. Geomorphological mapping was performed using multibeam bathymetric data and seismoacoustic profiling. The identified landforms include two types of transverse ridges interpreted as terminal and annual moraines, flat areas that are depressions filled with glaciomarine sediments, iceberg-generated pits and ploughmarks, pockmarks and fields of megaripples. Most of the identified landforms are genetically related to the retreat of Hansbreen since the termination of the Little Ice Age at the beginning of the twentieth century. Although Hansbreen has been speculated to be a surge-type glacier, no evidence of surging was identified in the submarine landform assemblage, which is in accordance with the absence of historically documented surges for that period.

## 1. Introduction

The submarine relief of fjords in the Arctic is a result of interactions of multiple factors including geological setting, tectonics, erosion, deposition, as well as processes beneath and in front of tidewater glaciers. Approximately 36,600 km$^2$, i.e. ~60% of the Svalbard archipelago, are covered by glaciers (Błaszczyk, Jania, & Kolondra, 2013). Most of the glaciers have been retreating since the end of Little Ice Age (LIA) at the turn of the nineteenth to twentieth centuries, (e.g. Błaszczyk et al., 2013; Martín-Moreno & Allende-Álvarez, 2016). However, according to various estimates, 13% to over 90% of them are surge-type glaciers (e.g. Błaszczyk et al., 2013; Farnsworth, Ingólfsson, Retelle, & Schomacker, 2016; Jiskoot, Boyle, & Murray, 1998; Lefauconnier & Hagen, 1991), i.e. they undergo cyclic rapid advances followed by retreats. Because knowledge of past glacier behaviour remains sparse due to limited historical and monitoring data, geomorphological studies on land (e.g. Ewertowski, Evans, Roberts, & Tomczyk, 2016; Karczewski et al., 1984) as well as on the seafloor (e.g. Dowdeswell & Ottesen, 2016; Ottesen & Dowdeswell, 2006; Plassen, Vorren, & Forwick, 2004) are useful sources of information of past glacial activity.

In this paper, we focus on the submarine relief in front of the tidewater glacier Hansbreen (Figure 1). Even though Hansbreen is among the best-studied glaciers in Svalbard, it remains unsolved whether or not it is a surge-type glacier. The latter are characterised by non-climate-related increase of the flow rate by at least an order of magnitude, which often results in glacier-front advance (Jania, 1997; Kristensen & Benn, 2012). There is no historical evidence of surging of Hansbreen (Błaszczyk et al., 2013). However, according to Jania (1998), advances of the glacier front in 1936–1938, 1957–1959, 1973–1977, 1982–1984 and 1993–1995 could have been mini-surges that resulted in the formation of small submarine moraines in the adjacent Hansbukta. Moreover, the observed shapes of the ice front and accelerations of glacier flow were indicative of surge-type glaciers (Jania & Głowacki, 1996). However, glacigenic structures and terrestrial landform-assemblage analyses led Rachlewicz and Szczuciński (2000) to conclude that there is no evidence of surges.

Farnsworth et al. (2016) classified most of the glaciers on Svalbard, including Hansbreen, as surge-type glaciers on the basis of crevasse-squeezed ridges identified on satellite images. However, their landform interpretations contradict fieldwork-based geomorphological work in the area (Karczewski et al., 1984; Karczewski, Rachlewicz, & Szczuciński, 2003; Rachlewicz & Szczuciński, 2000; Skolasińska, Rachlewicz, & Szczuciński, 2016). Submarine landform assemblages beyond the termini of multiple glaciers on Svalbard
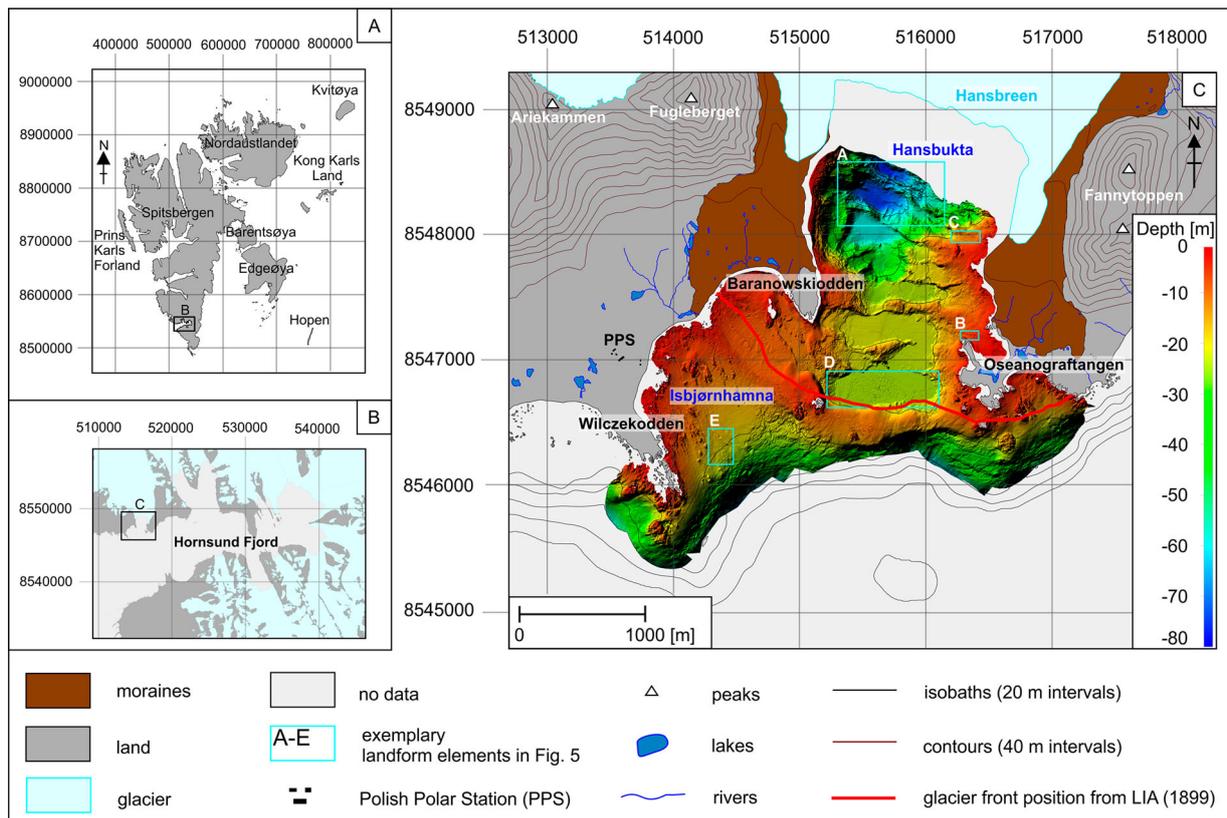
**Figure 1.** Study area. (A) Location of the study area within Svalbard; (B) – Study area within Hornsund Fjord; (C) Isbjørnhamna and Hansbukta bathymetry after the Main Map. The boxes named 'a' to 'e' refer to the locations of the landforms presented in detail in Figure 5. Sources: Norwegian Polar Institute: http://geodata.npolar.no/ and swath bathymetry data from Norwegian Hydrographic Service (permit no. for IG PAS: 13/G722).

provide information on their surge histories (Ottesen et al., 2008; Ottesen & Dowdeswell, 2006; Streuff, Forwick, Szczuciński, Andreassen, & Ó Cofaigh, 2015). However, even though the general bathymetry off Hansbreen has been studied earlier (Görlich, 1986; Tęgowski, Trzcińska, Kasprzak, & Nowak, 2016), detailed geomorphological analysis of the seafloor remains to be performed.

The aim of our study is to present and analyse new bathymetric, backscattering and geomorphological maps of the seabed of the glacial bays Hansbukta and Isbjørnhamna in front of the tidewater glacier Hansbreen in southwestern Spitsbergen (Figure 1). The seismoacoustic data were used to make the geomorphological map, too. These data are integrated with known glaciological and geological/geomorphological data, with the purpose of reconstructing the glacier dynamics during the past ~120 years, including the evaluation whether or not the Hansbreen is a surge-type glacier.

Hansbreen is among the best-studied glaciers on Spitsbergen (e.g. Błaszczyk et al., 2013; Gajek, Trojanowski, & Malinowski, 2017; Vieli, Jania, & Kolondra, 2002). This knowledge about that glacier may allow a better understanding of the past activity of Hansbreen and link it with the formation of submarine landforms.

## 2. Study area

The study area includes two bays, Isbjørnhamna and Hansbukta, which are located in the northern part of the Hornsund Fjord in southwestern Spitsbergen (Figure 1). The maximum water depths in Isbjørnhamna and Hansbukta exceed 20 and 80 m, respectively. At the end of the LIA, Hansbreen terminated in the eastern part of Isbjørnhamna, whereas Hansbukta was entirely covered by the glacier (Błaszczyk et al., 2013) (Figure 1). During the post-LIA retreat, Isbjørnhamna became glacier-free and its shore has been modified mainly by tides and waves. The latter has resulted in significant coastal erosion, resulting in land losses exceeding 28,000 m² between 1960 and 2011 (Zagórski et al., 2015). Meanwhile, Hansbukta was formed due to the glacier retreat. The retreat rate of Hansbreen varied from 28 m/year (1982–1990), when it was pinned to a shallow bedrock sill, to 280 m/year (1990/1991), when the ice front retreated over relatively deep water (Vieli et al., 2002). The present average retreat rate of Hansbreen is approximately 40 m/year (Błaszczyk, Jania, & Hagen, 2009). However, seasonal variations in the glacier-front position of 50–190 m have occurred due to intensive calving in summer and reduced melting and calving during winter (Błaszczyk et al., 2013).

Most of the terrain adjacent to the studied bays is covered by a thin (usually less than 1 m) cover of glacigenic sediments composed of subglacial and supraglacial tills and glacifluvial deposits (Karczewski et al., 1984; Karczewski et al., 2003; Rachlewicz & Szczuciński, 2000; Skolasińska et al., 2016). These cover bedrocks of low to intermediate grades of metamorphism (Birkenmajer, 1990; Czerny, Kieres, Manecki, & Rajchel, 1993). The most common rock types are schists, gneisses, amphibolites, marbles and quartzites. They belong to several stratigraphic units characterised by N–S strike directions (Figure 2). At least three faults are identified in the study area (Figure 2). Two of these

are NNW-SSE striking normal faults occurring in the NE part of Isbjørnhamna. The third is an N–S striking thrust fault that affected the bedrock beneath the western part of Hansbreen. All of them probably continue under the seabed (Czerny et al., 1993; Dallmann & Tesfamariam, 2015) (Figure 2).

## 3. Data, methods and map production

### 3.1. Multibeam data and processing

Swath bathymetry data were acquired by the Norwegian Hydrographic Service in 2007 using a Kongsberg
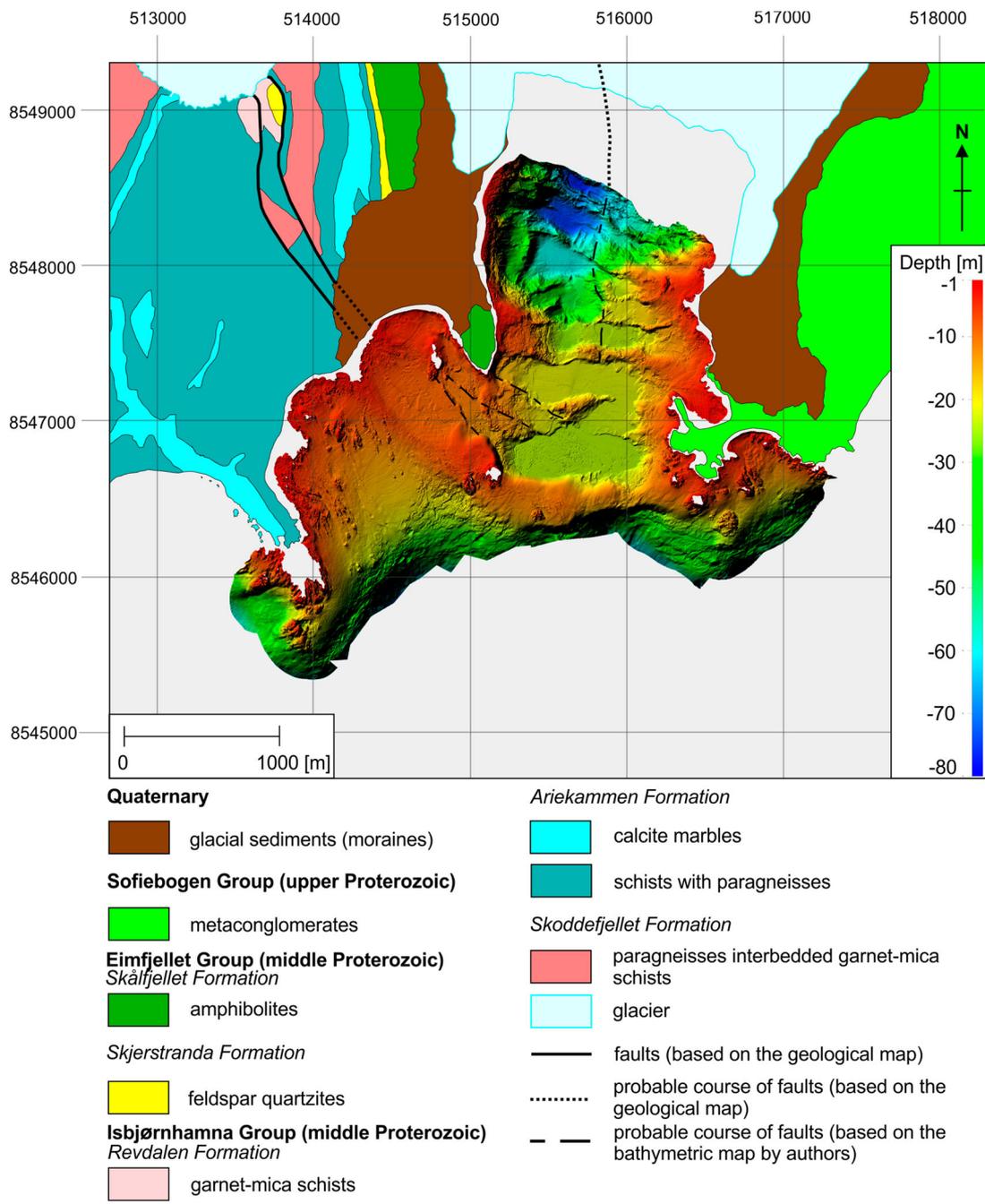


**Figure 2.** Bedrock and Quaternary geology around Isbjørnhamna and Hansbukta (after Birkenmajer, 1990; Czerny et al., 1993 and Majka, Czerny, Mazur, Holm, & Manecki, 2010). Bathymetry after the Main Map.

3002 multibeam echosounder with the following parameters: frequency 300 kHz, opening angle 200° and number of beams 508 (permitted for use by the Institute of Geophysics Polish Academy of Sciences under permit number 13/G722). Tidal and sound-velocity profile corrections were applied by the Norwegian Hydrographic Service. The topographic, vector-type data of land area are collected by the Norwegian Polar Institute in 1990 (http://geodata.npolar.no). However, the present extent of Hansbreen and the locations of moraines are based on Landsat 8 satellite images obtained on 1 October 2015.

The Global Mapper v16.0 software program (GM) was used for swath bathymetry data interpolation, as well as to produce a digital terrain model and maps. We applied Triangulation (Grid TIN of Points) as the gridding method. For the grid spacing, we used 0.5 m by 0.5 m and Filter/Noise/Median (4 × 4) with a sample spacing 0.5 m was used for resampling. The bathymetric map was produced at a scale of 1:10,000 using the WGS 84 datum and UTM projection zone 33N (Main Map A). Multiple sub-parallel linear features were found on the bathymetric map. We interpret them as artefacts from refractions and wobbly outer beams. They may be due to using an inappropriate sound-velocity profile or natural and human acoustic noise sources (Jakobsson et al., 2016). The water column structure at the front of the tidewater glacier is variable so it is hard to apply a single proper sound-velocity profile. The bathymetric map was used to perform slope and slope direction maps in GM using the Slope Shader and Slope Direction Shader commands (Figure 3(A,B)). These maps are used to verify the shapes of the geomorphological landforms, as well as to provide information about the stability of sediments (Moskalik, Pastusiak, & Tęgowski, 2012, 2013).

The backscattering (Main Map B) allows sediment-type classification. Backscattering (dB) is the multibeam echosounder's signal reflection from the seabed that depends primarily on the type of seafloor (bedrock and sediments), beam angle and other factors (Jakobsson et al., 2016; Lamarche, Lurton, Verdier, & Augustin, 2011). The raw backscattering data with coordinates were extracted using the MB-System software (http://www.mbari.org/products/research-software/mb-system/). They were prepared in Matlab before creating the backscattering map in GM. The data processing in Matlab included: converting the geographical coordinates to the Universal Transverse Mercator (UTM), followed by downscaling of the resolution to a 1-m grid. For coordinates with overlapping beams, the mean value was used. Artefacts occur also on the backscattering map (Main Map B). Their occurrence mainly depends on the grazing angle, properties of the positioning and motion sensors, the seafloor geometry and water properties (Montereale-Gavazzi et al., 2017). Comparisons with existing sedimentological data (Görlich, 1986)

and own unpublished grain size data on surface sediment samples allowed us to assign the lower values of backscattering (approximately −30/−40 dB) to fine-grained sediments (mud) and higher values (−15/−20 dB) to coarse-grained sediments (sand and gravel) or bedrock. All the gathered data and maps were used to interpret the geomorphological forms presented with a 1-m resolution in Main Map C.

The geomorphological and backscattering maps were produced at a scale of 1:20,000 using the same datum and projections as the bathymetric map.

## 3.2. Sub-bottom data and processing

The seismoacoustic profiling was performed in Hansbukta in July 2016 using an EdgeTech sub-bottom profiler SB-216S operating at frequencies of 2–15 kHz and a ping rate of 4 Hz (Figure 4). The profiles were analysed using Discover Sub-Bottom 4.09, employing multiple Time-Varied Gain (TVG) and Gain settings. TVG and gain depend on water depth and signal strength. A sound velocity of 1500 m/s, both in the water and sediments, was used to convert two-way travel time in milliseconds to depth in metres.

## 3.3. Remote sensing data

Landsat satellite images (acquired between 1976 and 2009) were used to determine the locations of the glacier fronts in selected years (Figure 4(A)). Only satellite images without clouds were used.

## 4. Results and discussion

Based on the analyses of bathymetric, backscattering, seismoacoustic, slope angle and slope directions data, the following types of submarine relief were distinguished: a large transverse ridge, moderate-size transverse ridges, fields of regular small ridges, flat-floored depressions, circular and elongated depressions, and irregular slopes.

## 4.1. Large transverse ridge
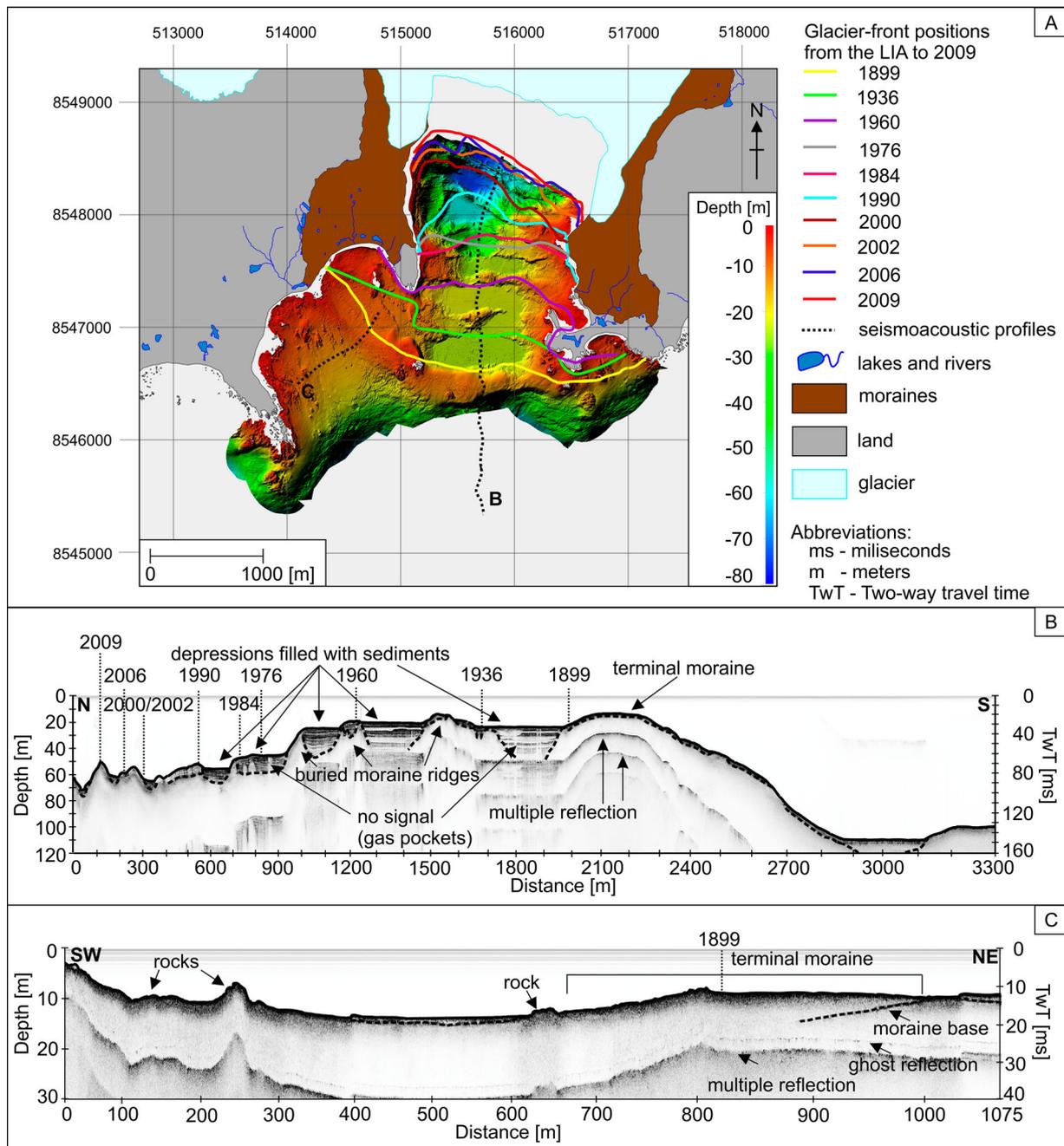
### 4.1.1. Description

A large transverse ridge at the mouth of Hansbukta is the most prominent single landform. It is located approximately 2.5 km off the modern ice cliff. It is part of a continuous ridge system and it connects two onshore moraines on the western and eastern side of Hansbukta, respectively (Figure 1). The length of the underwater part of the ridge is close to 3 km, and its total area is approximately 1 km². Its width ranges from 100 m in Isbjørnhamna to approximately 300 m in Hansbukta. The ridge height varies between 3 and 13 m; it is lower in Isbjørnhamna than in Hansbukta (Figure 1). The top of the underwater part of
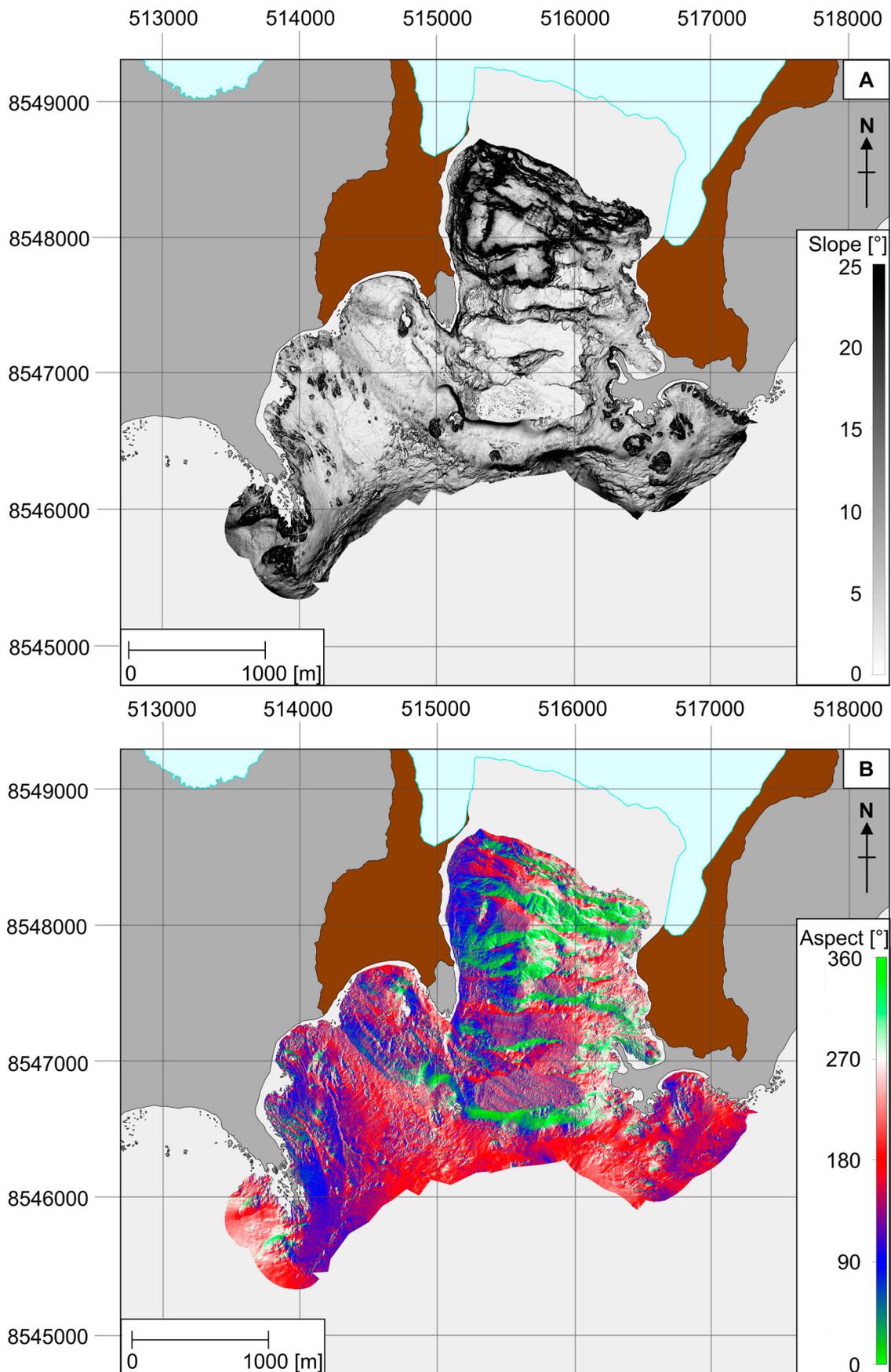
**Figure 3.** Slope characteristics in Isbjørnhamna and Hansbukta. (A) Slope inclination; (B) slope aspect.

the ridge is mainly plain and it is located at water depths ranging from about 10 to 25 m. The slope angles are between 2° and 25°. The steepest part of the ridge is in Hansbukta (Figure 3). In Isbjørnhamna, the distal slopes are gentler than the proximal slopes (Figures 3 (A) and 4(C)).

**Figure 4.** (A) Bathymetric map of Isbjørnhamna and Hansbukta with marked glacier-front positions for selected years and the locations of the seismoacoustic profiles. (B) Seismoacoustic profile with interpretation in Hansbukta; (C) Seismoacoustic profile with interpretation in Isbjørnhamna. The numbers (years) provided in (B,C) refer to glacier-front positions. The distance scales on (B,C) differ.

### 4.1.2. Interpretation

The submarine ridge is interpreted as a terminal moraine, whereas the ridges on land are lateral moraines (Main Map C). Their morphology is similar to the lateral and terminal moraines of Kollerbreen (Burton, Dowdeswell, Hogan, & Noormets, 2016). Taking into account the size, morphology, continuation on land in the form of a terminal/lateral moraine (Błaszczyk et al., 2013; Karczewski et al., 1984; Kozarski, 1982), as well as the resemblance to moraine systems in other parts of Spitsbergen (e.g. Boulton, 1986; Flink, Noormets, & Kirchner, 2016; Kempf, Forwick, Laberg, & Vorren, 2013; Ottesen et al., 2008; Ottesen &

Dowdeswell, 2006; Plassen et al., 2004; Streuff et al., 2015, 2017), we interpret the large transverse ridge as a terminal moraine marking the maximum glacier extent at the end of the LIA (Błaszczyk et al., 2013) (Main Map A, C). On the basis of the backscattering data, we infer that its surface is mainly composed of coarse sediments (Main Map B).

### 4.2. Moderate-size transverse ridges

#### 4.2.1. Description

Several moderate-size transverse ridges are oriented sub-parallel to the modern glacier front in the deep,

inner part of Hansbukta. The longest ridge is approximately 1.1 km long. Their maximum widths and heights are approximately 100 and 10 m, respectively (Figure 5(A,F)). They occur in water depths from 20 to ~80 m. They have lower heights in their central parts and near the glacier cliff and higher near the shores of Hansbukta. Several ridges have significantly lower heights in the central part of the bay. In some parts, they are only approximately 0.5 m high. Some ridges appear to be partly discontinuous (Figure 5 (F)). Their slopes can exceed 25° (Figure 3).

### 4.2.2. Interpretation

We interpret these features as recessional moraine ridges (Main Map C) that possibly formed during winter stillstands or minor readvances, as also reported from other fjords on Svalbard (e.g. Baeten, Forwick, Vogt, & Vorren, 2010; Boulton, 1986; Flink et al., 2015, 2016; Ottesen et al., 2008). The well-preserved ridges correspond to the glacier-front positions in 1960, 1976, 1984, 1990, 2000/2002, 2006 and 2009 (Figures 1(C) and 4(A,B)). The ridges deposited in 1976 and 1984 correspond to years with the mini-surges described by Jania (1998). The limited number of ridges could have been caused by more extensive winter readvances during some years, when the grounded glacier overrode and destroyed older ridges. It is also possible that during some years the winter readvance was too weak to create a new moraine. Some parts of the moraine ridges are buried by glacimarine sediments (Figure 4(B)).
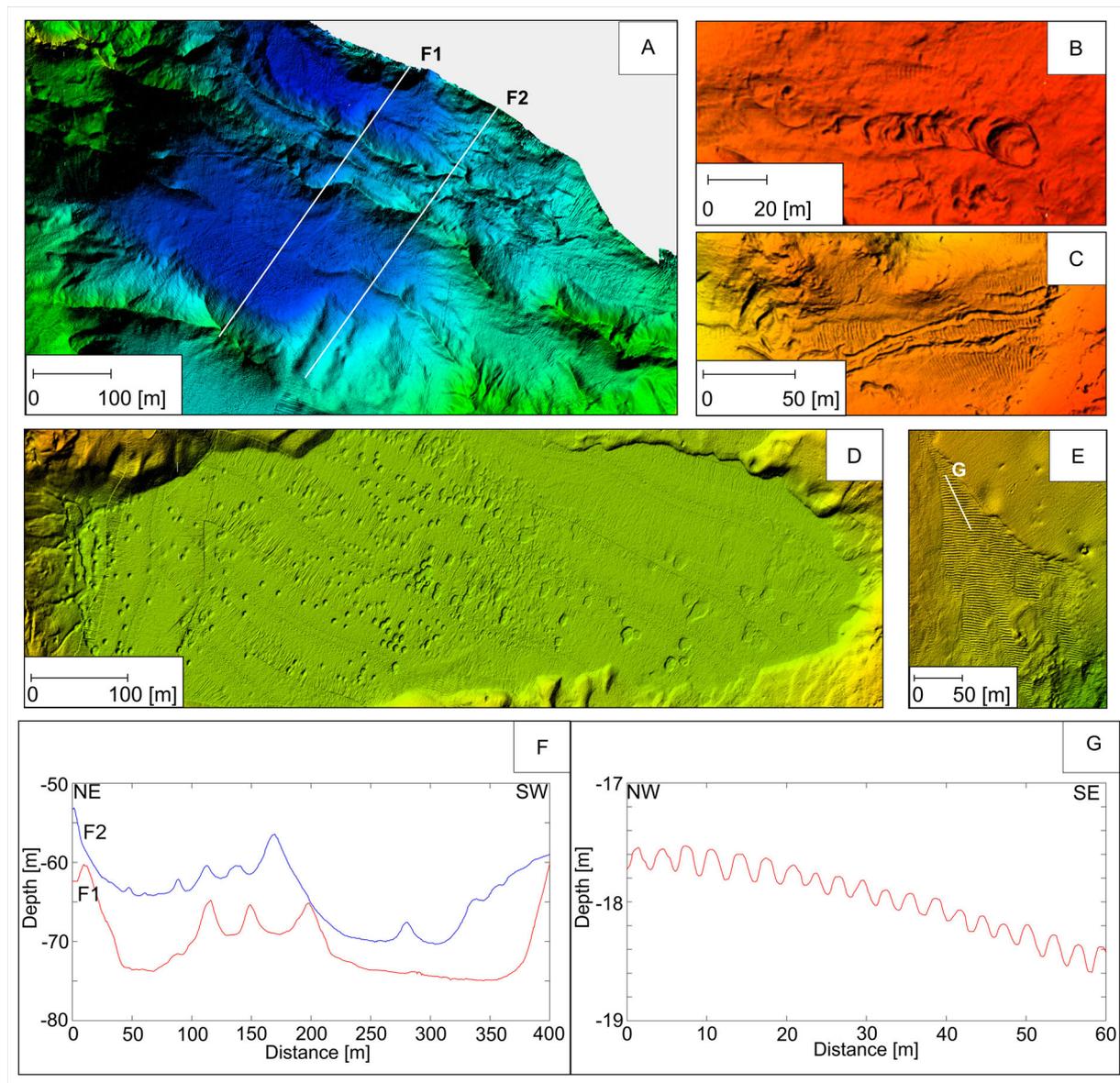


**Figure 5.** Details of selected morphological features. For the location, see Figure 1. (A) Moderate-size moraine ridges with adjacent flat-floored areas; (B) Example of a chain of iceberg-generated pits; (C) Iceberg-generated ploughmarks; (D) Pockmarks on the flat-floored area; (E) Field of megaripples, (F) Morphological profiles across moderate-size moraines (marked on Figure 5(A)); (G) Profile across the field of megaripples (marked on (E)).

## 4.3. Fields of regular small ridges

### 4.3.1. Description

In shallow parts of the bays (<25 m), approximately 130 fields of small ridges were found (Figure 5(E)). Their total area is 0.29 km$^2$. The heights of the individual ridges are less than 0.3 m and the distances between ridges range from 1.5 to 3.5 m. The orientation of their crests is roughly W–E (Figure 5(G)).These structures are present in various landform associations, e.g. on the top surface of the terminal moraine, between underwater rocks and the terminal moraine in Isbjørnhamna, as well as along eastern shore of Hansbukta. The strength of the backscattering signal reflection in the place of occurring of these fields differs from the surroundings, and their boundaries correspond to borders seen on the backscattering map (Main Map B, C), in particular in Isbjørnhamna.

### 4.3.2. Interpretation

The described forms resemble ripplemarks (Main Map C). The direct observations by divers (e.g. co-author M. Moskalik) confirm that interpretation. Due to their sizes, these forms are classified as megaripples (Passchier & Kleinhans, 2005). Because these ridges are almost symmetrical, they could be considered to be wave-generated (Chang & Flemming, 2013). Taking into account the typical moderate ocean swell parameters (Wojtysiak, Herman, & Moskalik, 2018), it is likely that the forms are modified only during the storms. Available time-lapse images of Isbjørnhamna taken from Ariekammen in 1-hour intervals by staff of The Polish Polar Station in Hornsund reveal swell with waves lengths >100 m in Isbjørnhamna. Thus, the megaripples are interpreted as formed by storm-generated swell waves. The backscattering values for ripplemarks range from −25 dB to ∼ −15 dB and are typical for moderate to coarse-grained sediments confirmed by visual observations during the dives (Main Map B, C).

## 4.4. Flat-floored depressions

### 4.4.1. Description

Five flat areas were found at water depths between 20 and 70 m in Hansbukta. They are separated by moderate-size transverse ridges (Figures 1, 4(B), 5(A,D)). Their total area is approximately 0.61 km$^2$, and the areas of the individual features vary between 0.02 and 0.43 km$^2$. The largest depression is located near the mouth of Hansbukta and consists of two parts, which are partly separated by a high-backscatter ridge (Main Map A,C). The N–S and E–W extents of the flat areas are from ∼135 to ∼700 m and from ∼200 to ∼860 m, respectively (Figure 5(D), Main Map A, C). Their surface reveals medium and low backscattering values (from ∼ −40 dB to ∼ −25 dB) (Main Map B). The seismoacoustic profiles revealed that the flat areas are basins filled with stratified deposits ranging in thickness from 25 m in the outer depression (near the terminal moraine) to approximately 10 m in the most glacier-proximal basin (Figure 4(B)).

### 4.4.2. Interpretation

The flat-floored depressions are interpreted to be depocentres filled with sediments (e.g. Dowdeswell & Vasquez, 2013; Ottesen & Dowdeswell, 2009) (Main Map A, C). The sediments derive mainly from overflow plumes from Hansbreen. In addition, the bottom currents could lead to sediment redistribution from shallower areas (Forwick et al., 2010). As the velocity of bottom currents of Hansbukta range between 10 and above 15 cm/s (Moskalik et al., 2018), this process appears feasible. Assuming that the glacier was grounded, using the information of the basin-infill thicknesses and the time of glacier retreat from the particular basins, we estimated that the mean sediment accumulation rates (SAR) in the depressions vary between 25 and 40 cm /year (Figure 4(A,B)). Previous works in Hansbukta suggested SAR to be over 20 cm/ year close to the front of Hansbreen (Görlich, 1986) and less than 0.8 cm/year south of the terminal moraine (Pawłowska et al., 2017). Given this marked decrease in SAR, the depressions were likely filled with sediments when the ice front position was very close to them. The depressions are filled with the fine-grained and mixed-grain size sediments (Main Map B). The acoustic stratification visible in the seismoacoustic profiles (Figure 4(B)) reflects repeated changes in acoustic impedance that are most probably related to changes in grain size, that typically occurs in glacier-proximal settings (Elverhøi, Lønne, & Seland, 1983; Forwick & Vorren, 2010; Ó Cofaigh & Dowdeswell, 2001).

## 4.5. Circular depressions

### 4.5.1. Description

Two types of circular depressions have been identified. The first type is characterised by slightly elongated, predominately single depressions, mainly at water depths shallower than 20 m. They occur between Wilczekodden and the terminal moraine in Isbjørnhamna, as well as on the distal slope of the moraine, which does not exceed 10° in that place. Another area with similar features occurs near the east coast of Hansbukta. There, the depressions appear as single forms or in chains in water depths shallower than 15 m. The diameters of these single features range from less than 2 m to above 20 m. Their average diameter is 7 m. Approximately 300 circular depressions covering a total area of ∼0.025 km$^2$ have been identified.

The second type is characterised by more than 380 symmetrical circular depressions that occur on the flat-floored depression near the terminal moraine, at water depths of ∼25 m. Diameters vary between 1

and approximately 10 m (Figure 5(D)). Their depths range from 0.1 to 1 m, with a mean of ∼0.35 m. Their inner slope angles vary between 10° and 40° (Figure 3(A)). They are concentrated in the western and central parts of the most distal flat area and occupy 0.012 km². They are more clearly outlined in areas covered by fine-grained sediments (Main Map B). The seismoacoustic signal disappears below the surface covered with these features (Figure 4(B)).

### 4.5.2. Interpretation
The shape of the elongated pits is similar to shallow-water pits in, e.g. Billefjorden that were interpreted as iceberg-generated pits (Main Map C) (e.g. Baeten et al., 2010). The depth of occurrence of pits is related to the keel depths of the icebergs. Their occurrence along the eastern shorelines is related to the drift by the oceanic swell. The icebergs can be repeatedly grounded on the shallow seabed during low tide and are then lifted and relocated during the following flood tide, thus leading to the formation of pit chains. The pits in Isbjørnhamna are in deeper water and were likely created by larger icebergs that drifted from the inner Hornsund fjord. The shallow crest of the terminal moraine, as well as the shallow area between Isbjørnhamna and Hansbukta prevented these large icebergs from entering Hansbukta. The pits located in Hansbukta are formed by icebergs from Hansbreen. The depressions concentrated on the flat area in Hansbukta are interpreted as pockmarks (Forwick, Baeten, & Vorren, 2009; Roy, Hovland, & Braathen, 2015) (Main Map A, C). Due to the small sizes, these forms are classified as unit-pockmarks (Hovland, Heggland, De Vries, & Tjelta, 2010). Compared to the pits, these features are more symmetrical and occur only in a single flat area surrounded by shallower areas, which exclude an iceberg origin for these depressions. They can form due to submarine freshwater outflows, thermogenic and biogenic filtration of gases or in association with gas migration from the faults (Forwick et al., 2009; Rogers, Kelley, Belknap, Gontz, & Barnhardt, 2006; Sun et al., 2011). The lack of seismoacoustic signals in sediments below pockmarks can be related to water escape due to high sedimentation rates (Ottesen et al., 2008) as well as the seepage of gas (Forwick et al., 2009) (Figure 4(B)). The formation mechanisms of the pockmarks in the study area remain to be identified. They could have formed due to gas migration along faults (Figure 2), or they could have formed due to water escape related to very high sedimentation rates (Ottesen et al., 2008) (Figure 2).

### 4.6. Elongated depressions

### 4.6.1. Description
Multiple elongated depressions (furrows) occur in the shallow parts of the study area, primarily shallower than 10–15 m water depth in the eastern part of Hansbukta and on the slopes of Isbjørnhamna (Figure 5(B, C)). Their lengths range is from approximately 10 to 155 m, and their widths do not exceed 5 m. They occur often in groups and within the areas from where iceberg pits have been described. The furrows in Isbjørnhamna are typically longer than in Hansbukta. They occur in places where the reflected signal strengths are between −30 dB and −20 dB (Main Map B). Altogether, more than 150 furrows were documented.

### 4.6.2. Interpretation
The furrows are interpreted as iceberg ploughmarks (Main Map A, C) that were formed by icebergs keels 'ploughing' the seafloor (e.g. Woodworth-Lynas, Josenhans, Barrie, Lewis, & Parrott, 1991; Dowdeswell & Vasquez, 2013). These forms are on the seafloor in places composed of relatively fine-grained sediments (Main Map B). The largest ploughmarks are found in deeper water in Isbjørnhamna and are likely related to large icebergs that drifted from the inner fjord. The common east–west-oriented furrows in the Hansbukta are likely related to the swell-driven drift direction. Their occurrence at water depths similar to those of the iceberg pits suggests that they may have formed from the same icebergs that partly remained stable (iceberg pits) or moved (iceberg ploughmarks).

### 4.7. Unassigned slopes

### 4.7.1. Description
Fourteen areas, with a total area of 1.08 km², occur at water depths between ∼20 to ∼60 m, on slope angles of approximately 30° (near Wilczekodden) (Main Map A,C). Some of the slopes have irregular surfaces and are partially covered by ploughmarks and pits. The backscattering values in these areas range from ∼ −40 dB to ∼ −25 dB (Main Map B,C).

### 4.7.2. Interpretation
Given the occurrence on steep slopes and irregular surfaces, we suggest that these areas have been exposed to mass wasting, as documented for other Svalbard fjords (e.g. Forwick & Vorren, 2011). The surfaces of the slopes are covered with fine-grained and mixed sediments.

### 4.8. Comparison with other tidewater-glacier settings on Svalbard

Most of the well-documented submarine landform assemblages in the inner parts of Svalbard fjords are related to glacier surges (e.g. Dowdeswell & Ottesen, 2016; Flink et al., 2015, Flink, Hill, Noormets, & Kirchner, 2017; Ottesen & Dowdeswell, 2006; Ottesen et al., 2008; Streuff et al., 2015). They share a number of

common features, including streamlined glacial lineations, overridden recessional moraines, crevasse squeeze ridges, transverse annual retreat moraines, eskers and rhombohedral ridges. Moreover, they include glacier surge terminal moraines often associated with lobe-shaped debris flows on their distal slopes.

Most of these characteristic surge-related landforms are absent on the seafloor off Hansbreen. Notably, there are no crevasse squeeze ridges, which are considered to be the most typical feature related to surging glacier. In fact, only a series of moderate-size transverse ridges may reflect some minor advances ('mini surges'), as discussed by Jania (1998). The submarine landform assemblage observed in Isbjørnhamna and Hansbukta presents a case for a relatively slowly retreating tidewater glacier (40 m/year on average) with no obvious surge events. The assemblage consists of glacial features (moraine ridges), evidence of rapid glaciomarine deposition (flat-floored basins), relief affected by the presence of icebergs (pits and ploughmarks), as well as features formed from non-glacial processes, i.e. megaripples, and pockmarks.

## 5. Conclusions

The presented bathymetric, backscattering and geomorphological maps from Isbjørnhamna and Hansbukta in the Hornsund Fjord, southwestern Spitsbergen, reveal a submarine relief and sediments formed by glacial processes, wave action, fluid release and mass wasting processes. The identified submarine landforms include a large transverse ridge interpreted as an LIA terminal moraine, smaller transverse ridges interpreted as minor moraines formed during minor winter advances and/or halts, iceberg-generated pits and ploughmarks, flat-floored depressions areas due to the rapid deposition of fine-grained sediments, megaripples and pockmarks. In accordance with historical data (Błaszczyk et al., 2013) and previous geomorphological works on land (Rachlewicz & Szczuciński, 2000), the new results support the conclusion that Hansbreen has not surged during the last ~ 120 years. Thus, the documented submarine landform assemblage may be considered as typical for a retreating (40 m/year) non-surge-type tidewater glacier in Svalbard.

## Software

MB-System (http://www.mbari.org/products/research-software/mb-system/) was used to obtain the backscattering data from the raw multibeam data. Matlab was used in the next step to prepare the Backscattering Map. Global Mapper v16.0 was used to make the digital terrain model and slope and aspects maps and to mark the glacier extents based on the satellite images from Landsat 8 and the literature. The final maps were produced using that software. The Discover Sub-Bottom 4.09 software program was used to analyse the seismoacoustic profiles. The resulting Main Map and figures were edited in CorelDraw Home Student X7.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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