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SUBMARINE EVIDENCE OF THE LATE WEICHSELIAN MAXIMUM EXTENT AND THE LITTLE ICE AGE (LIA) GLACIER LIMITS IN THE ST. JONSFJORDEN REGION (SVALBARD)

Abstract: The paper presents the results of bathymetric mapping of selected tidewater glaciers in the St. Jonsfjorden (Svalbard) between 2004 and 2007. We also used the bathymetric data collected by the Norwegian Hydrographic Service (NHS) as well as the shaded relief images based on them. The most clearly visible traces in submarine marginal zones of the glaciers come from the Little Ice Age (LIA), i.e. the cooling period which in the area of St. Jonsfjorden might have ended no later than about 1900. At the beginning of the 20th century, i.e. during a warm period, the glaciers of St. Jonsfjorden reached their maximums. The youngest traces in the sea-floor of the fjord and the bays date from this period, similar to the case of the land marginal zones. In front of the cliff of the Dahl Glacier there is a clearly visible zone of submarine moraines. It finishes exactly along the line of the LIA maximum. The sea-floor relief of the fjord and bays shows traces which we interpret as having been formed during the Late Weichselian (13–10 ka B.P.). At that time, the Dahl Glacier advanced onto the northern part of Hermansenøya; its main stream passed to the north of the island. Simultaneously, the Konow-Osborne Glacier terminated 2 to 4 km from the fjord mouth, leaving about 15 km² of the fjord ice-free.

Key words: Arctic, Svalbard, glacier, sea-floor morphology, push-moraines

Introduction

The analysis of the sea-floor of the fjord and bays poses an important issue for determining the glaciers' extension. Until recently, the previous extensions of glaciers were based on the existing moraines within the marginal zones existing on land. Within the sea bays the stretch of the ice-cliff was delimited approximately in the way so as to make a continuation of the glacial landforms. However, the results of the research in the Kaffiøyra region (Boulton 1986; Grześ et al. 2007a, b, 2008, 2009) as well as the sounding results in front of the cliff of the Hans Glacier in South Spitsbergen (Jania 1982, 1988, 1998; Kowalewski et al. 1987, 1991; Marsz 1993, 1996) indicate that there exist annual submarine push moraines. Their sequences lie apart from one another at a distance corresponding to the mean annual recession. These moraines are the consequence of cyclical, annual advances of ice-cliffs in winter, which pushed the deposits at the contact zone between the ice and the sea-floor. The development of larger forms might have been connected with surges (Jania 1986, 1988, 1998). The sea-floor relief of the fjord and bays also shows ramparts which are located directly along the extension of the ice-cliff. Such forms are connected with the LIA and older periods of glacier advances. The sea-floor relief is thus of great importance not only to the reconstruction of the glacial limits, but to the very dynamics of glacial processes as well. The sea-floor morphology either eased or limited the glacier's advance; it was also a factor which influenced the ice-cliff calving rate. The detailed morphology of the sea-floors of fjords and sea bays within marine marginal zones enables researchers to determine the directions and the dynamics of the glacial systems until Late Weichselian (Ottesen et al. 2007).

High-resolution bathymetric mapping of the fjords and continental shelf around the Svalbard archipelago show an extensive pattern of large- and medium-scale submarine landforms formed by differences in ice-flow regimes. Mega-scale glacial lineations, lateral moraines, transverse ridges and glaciotectonic features are superimposed on the large-scale fjord, shelf and cross-shelf trough morphology of the margin (Ottesen et al. 2007).

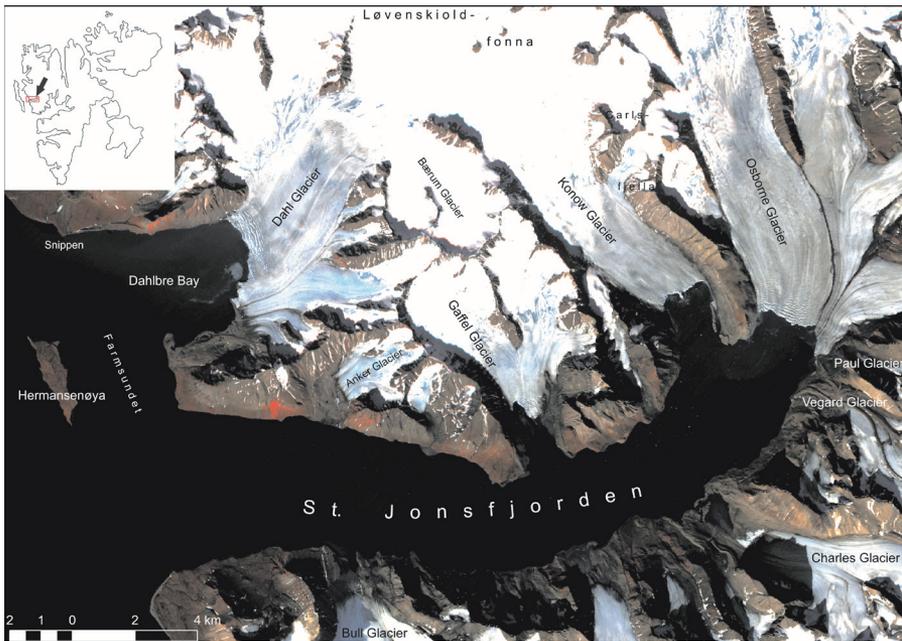


Fig. 1. Location map of the study area. St. Jonsfjorden, Spitsbergen. The map is based on two ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images, acquired in 2009. The map is presented as FCCs (False Colour Composites) of ASTER bands 321 as RGB

In this paper we try to interpret the submarine landforms as an indicator of glacial presence. We base our research on the shaded relief images generated from bathymetric data. In the years 2004–07 bathymetric data were collected from the sea-floors in front of the selected tidewater glaciers around St. Jonsfjorden.

St. Jonsfjorden is located in the central part of north-west Spitsbergen, half-way between two other large fjords: Isfjorden to the south and Kongsfjorden to the north (Fig. 1). St. Jonsfjorden is a part of the Oscar II Land, which in the south and south-east borders with Isfjorden, in the west with Forlandsundet, and in the north and east with the James I Land. This area, together with the entire north-east part of Spitsbergen as well as the Weddel-Jarlsberg Land, the Torell Land, the Olav V Land and Friesland, is among the most glaciated areas of Spitsbergen. The research included the Dahl Glacier, the Konow Glaciers and the Osborne Glacier.

Methods

The echo soundings of the forefields of the glaciers were conducted by means of an echo sounder which was integrated with a Garmin GPS Map 178C receiver. The potential error of any GPS measurement was 5 meters. Tidal changes, which can be as much as 1–2 m in the sea level, were disregarded. The Norwegian Hydrographic Service (NHS) collected single-beam echo sounder data during the years 1965–1994. The data cover the fjords, shelves and continental slope around Svalbard, in several areas down to more than 2000 m water depth. Data were gridded with a 37-m cell size. We used these data in the eastern part of the St. Jonsfjorden. Between 1999 and 2004, the NHS collected multi-beam bathymetric data of the fjords and the adjacent shelf areas around Svalbard. These data, to which we had access, cover the central and western part of the fjord. The data sets have been gridded with a 7-m cell size. For visualization, the data are presented as a colour-coded bathymetry map or black-and-white shaded relief images.

Results

Dahl Glacier

The Dahl Glacier is an outlet glacier, which starts at the Løvenskioldfonna (Fig. 1). Its area, together with the accumulation area and the branch glaciers, is about 110 km² (Błaszczuk et al. 2009). In the submarine marginal zone of the Dahl Glacier there is a clearly visible set of small transverse ridges (Fig. 2). Individual ridges are up to 15 m in height, have an average width of c. 50–150 m and are spaced a few hundred meters apart. These smaller ridges are fairly evenly spaced and are almost always found in clusters rather than as isolated individual features. Series of smaller transverse ridges are inferred to be moraines that record brief stillstands or winter-summer ice-front oscillations during general retreat of the ice margin at the time of deglaciation (Nygård et al. 2004; Ottesen and Dowdeswell 2006). The fact that these ridges contain volumes of debris several times smaller than large terminal ridges or grounding-zone wedges suggests that they are generally recording shorter-lived events during deglaciation (Ottesen et al. 2007). These retreat moraines are thought to be formed as push moraines during minor winter re-advances of a tidewater ice-front when iceberg calving is largely suppressed by the protecting presence of sea ice (Liestøl 1972; Boulton 1986; Ottesen and Dowdeswell 2006; Grześ et al. 2009). The retreat

moraines stretch about 3–4.5 km and finish at a distance of about 1.6 km from the north-eastern end of Hermansenøya. If we draw the marginal line of this zone of transverse ridges it will ideally correspond with the maximum extension of the glacier during the LIA. It can be assumed that the forms described above developed as a result of annual or seasonal oscillations of the ice-cliff of the Dahl Glacier during its recession, which started at the beginning of the 20th century (Lankauf 2002). The oldest forms are found at the distance of about 1.6 km from the Hermansenøya. At the end zones of these small transverse ridges individual forms are deformed. The distances between them are smaller, and distinctive traces of glacial lineation are missing. Here the depth of the sea decreases to 10–30 m. During the LIA the Dahl Glacier must have leant on its shallow zone, which posed a natural obstacle for the advancing glacier. This was a compression zone which stopped the further advancement of the glacier towards the south-west.

However, the glacier crossed this line during Late Weichselian (13–10 ka B.P.), as has been shown by Forman (1989) who noted series of Late Weichselian deposits in the cliff of the marine terrace (21 m above sea level) in the north end of Hermansenøya. They take the form of a layer (1–1.5 m) of lodgement till accumulated in the subaqual conditions, where the orientation of the longer axes of the clasts shows a north-easterly direction. This indicates that its development was connected with the glacier advancing from that direction, i.e. the Dahl Glacier (Forman 1989; Niewiarowski et al. 1993). As the age of shells of *Hiatella Arctica*, which are found in the sublittoral sands above the lodgement till (9825±90 years B.P. according to the radio-carbon dating; Forman 1989) indicates, the Dahl Glacier retreated from the north part of Hermansenøya before 10–10.5 ka B.P. According to Forman (1989), the precise extent of the expansion is not determined. The cliff might have ended in deep water (over 100 m) to the west of Hermansenøya.

On the basis of the evidence presented by Forman (1989), clearly visible glacial traces from Late Weichselian were expected in the surroundings of the island. Such traces would have been understandable as in many areas of Svalbard they are well preserved and are the main evidence for the reconstruction of both the directions and the dynamics of the glacial systems at that time (Ottesen et al. 2007). Despite that, however, there were no glacial traces discovered either to the east or to the west of the island. The situation in the northern part of Hermansenøya is diverse. About 300–400 m to the north of the island's axis there are forms which might have devel-

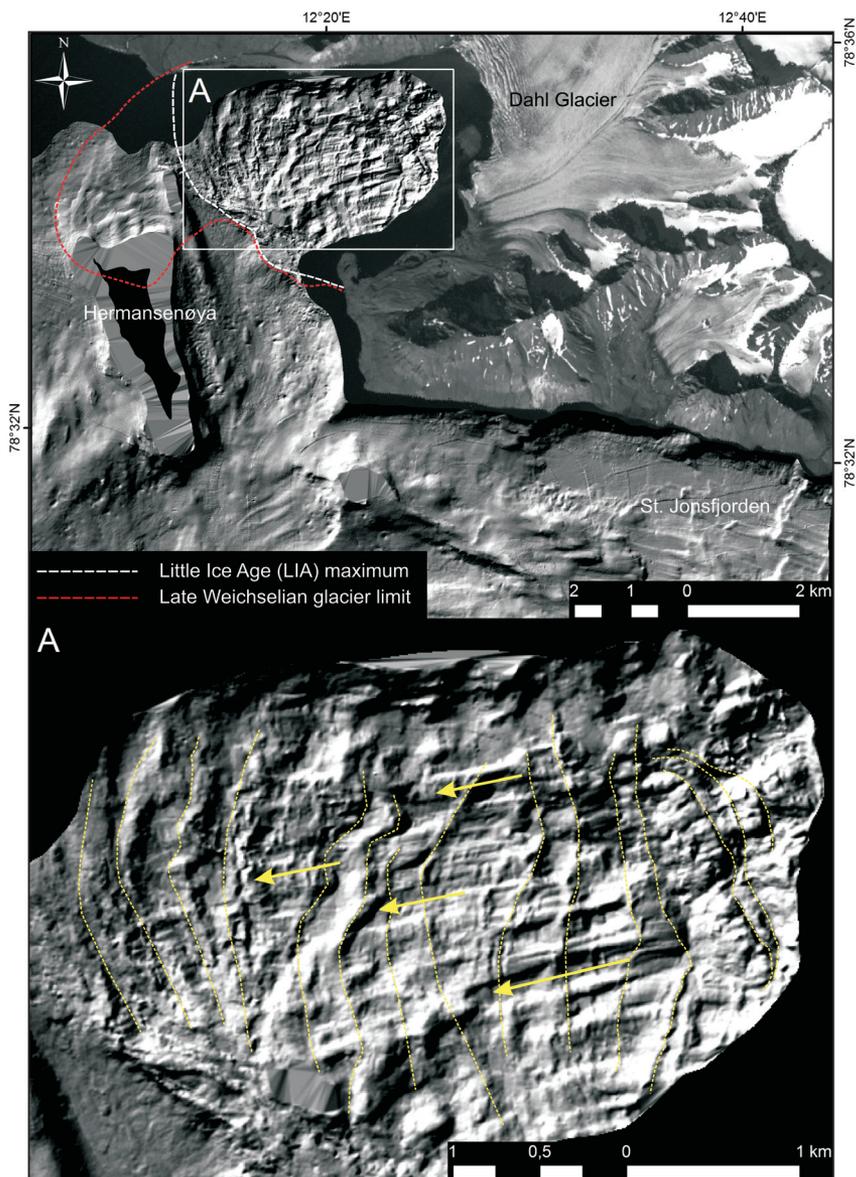


Fig. 2. Shaded-relief image of the Dahlbre Bay. Yellow dashed lines show forms interpreted as recessional moraines on a surface with glacial lineations. The direction of the ice recession was from south-west to north-east. Yellow arrows show the direction of the ice-cliff advance during the Little Ice Age (reproduced with the permission of the Norwegian Hydrographic Service, permission no. G641)

oped during the advance of the glacier in Late Weichselian. These are the ridges orientated north-east to south-west. Individual ridges are much more poorly visible than in the case of those which are found to the east of the maximum extension from the LIA. This may be the effect of the processes of washing out and lowering, which have been in force for the last 13–10 thousand years.

The presence of the forms of glacial relief to the north of the island gives new evidence of the evolution of glaciation of this part of Jonsfjorden during Late Weichselian (13–10 ka B.P.). Before that time the Dahl Glacier had not covered the entire area of the contemporary Hermansenøya. The glacier advanced only to the northern part of the island. It must be stressed that almost the entire island was under water at that time. Possibly only its central part was above water in the form of a steep-slope rock. During the expansion of the Dahl Glacier, its cliff was asymmetric. In comparison with the southern section, its northern part advanced further by about 2.5 km. Much larger extension of the ice in the northern section of the cliff of the Dahl Glacier was conditioned by two factors. Firstly, the northern part of the cliff was a typical cliff of submerged foot, which moved by about 220–240 m annually. Until recently (2006), the southern part was a cliff of a temporarily submerged foot and at present it is a typical front which has no contact with the water and moves 2–3 times slower. Moreover, the southern sea-floor zone, which was within the reach of the glacier during the Little Ice Age is now much shallower. During Late Weichselian this area was a natural obstacle which halted the glacier. Due to low velocity conditioned by increased friction this obstacle was never passed. The ice masses were moving by the much faster northern stream off Hermansenøya, which was moving towards south-west. The southern part of this stream reached the northern edge of Hermansenøya, while the central one ended about 600 m from the north-western edge of the island. This asymmetry was also significant during the glacier's advance throughout the Little Ice Age. At that time, the north part of the cliff advanced further by about 800–900 m.

Konow and Osborne Glaciers

The glaciers Konow and Osborne are outlet glaciers which end up the ice-cliffs in St. Jonsfjorden (Fig. 1). Their areas are 39.9 and 130.6 km², respectively (Błaszczuk et al. 2009). Since the 1960s, the Konow and Osborne

Glaciers have been single glaciers separated from each other by the massif of Karlsfjella mountain. Until then, they had one tongue of ice-cliff, which filled up the entire eastern part of St. Jonsfjorden. These glaciers have one accumulation area which is a part of Løvenskioldfonna located at the altitude of 400–500 m above sea level. Both of them are grounded. In relation to the maximum extent during the Little Ice Age (100%) the front zones of the Konow and Osborne Glaciers have been reduced by about 10%. These values are among the lowest for the entire area of Forlandsundet. Although the relative mean recession values are among the highest, these glaciers are among those which retreat at the slowest rate.

On the narrow shore zone on both sides of St. Jonsfjorden a rich complex of morainic forms has developed. The relief of the north side of the fjord is poorly diversified, while the south side has preserved a large number of forms. During the maximum extent at the time of the LIA they were disturbed by the advancing front sections of the glaciers Paul, Vegard and Charles. The relief of the sea-floor of St. Jonsfjorden in its individual sections is diverse, with depths varying in particular from its outlet to Forlandsundet. In the southern part down to 20 m, the sea-floor is lightly inclined in a northerly direction. Further on, a sudden increase in the depth down to 100 m is recorded. A steep submarine slope turns into a flat-bottomed basin located at a depth of 120–160 m. This basin stretches 2.5 km to the east until a submarine ridge of steep slopes is reached.

Next, 1.5 km off the north shore of the fjord there is a submarine ridge, the peak of which is several meters under water. It runs 5–6 km to the south-east. On the north side of the ridge there is a deep and narrow basin of up to 160 m in depth. In the central part of the fjord, at a depth of 120 m there is another basin separated from the above-mentioned basin by a ridge of up to 60 m above the sea-floor level. To the east of it, the depth decreases both in the central section and in the shore parts. About 1.5 km from the axis of the valleys of the glaciers Gaffel and Løvlie, along the entire width of the fjord there is a distinct ridge at a depth of 20–30 m. At the extension of this ridge, on both sides of the fjord there are morainic forms located on the terraces. They show the maximum extent of the Konow-Osborne Glacier during the maximum of the LIA (Preisner 1988). These forms are morainic hills stretching along a belt 350 m long and 120 m wide. These morainic hills are a few metres high and form arched sequences which correspond with the cliff's edge (Preisner 1988). The ridge, which stretches along the entire width of

the fjord, might have posed a natural obstacle to the advancing glacier. It is supposed that the ridge is covered with morainic material, which might have melted out from the bottom and inner parts of the glacier. During the maximum of the LIA some branch glaciers, including Paul, Vegard and Charles, were connected with the main ice-stream of the Konow-Osborne Glacier. As a result, there was a large amount of extra morainic material being transported to the main glacier. According to Preisner (1988) scattered morainic material, mainly coarse-grained, is present in the places distant from the shore, where it was transported by icebergs from the calving cliff. It was found out that both on the land and in the relief of the sea-floor of the fjord there are forms from the maximum advance of the Konow-Osborne Glacier during the LIA (Figs. 3, 4). Along the line of this limit there is a ridge on the sea-floor and the depth here is only 20–30 m. The ridge is most probably covered with the morainic material. During the maximum of the LIA this ridge, which is located across the entire fjord, must have been an obstacle which prevented the glacier from advancing further.

The situation was different during the Late Weichselian (13–10 ka B.P.). Despite a number of theories of the glaciation of St. Jonsfjorden at that time (Kverndal 1991; Evans and Rea 2005), the most probable evidence is given by Forman (1989). According to the author, the absence of pre-Late Weichselian raised beaches and lateral moraine remnant indicate that inner and mid St. Jonsfjorden were occupied by a glacier to at least 55 m above sea level. Five km in-fjord, the presence of lodgement till at 6 m and lateral moraine at 55 m indicate that glacier-ice actively moved over this area. Just beyond this area the Late Weichselian Marine Limit (LWML) rises from 35 to 45 m above sea level, coincident with the occurrence of pre-Late Weichselian raised beaches, suggesting that the glacier in St. Jonsfjorden terminated near this area, 2 to 4 km from the fjord mouth.

On the basis of the shaded relief images it was concluded that the relief of the bottom of the fjord shows distinct traces which allow the researchers to delimit the maximum extension of the Konow-Osborne Glacier 13–10 ka B.P. (Fig. 5). Submarine lineations are observed in the inner and mid. part of St. Jonsfjorden. The lineations occurred 5–9 km from the fjord mouth and are north-west orientated. They vary from hundreds of meters to few kilometers in length. The distance between each form is from one hundred up to a few hundred meters and elevation is about 2 meters. It means that these forms are sedimentary bedforms rather than sculpted bedrock. The lineations

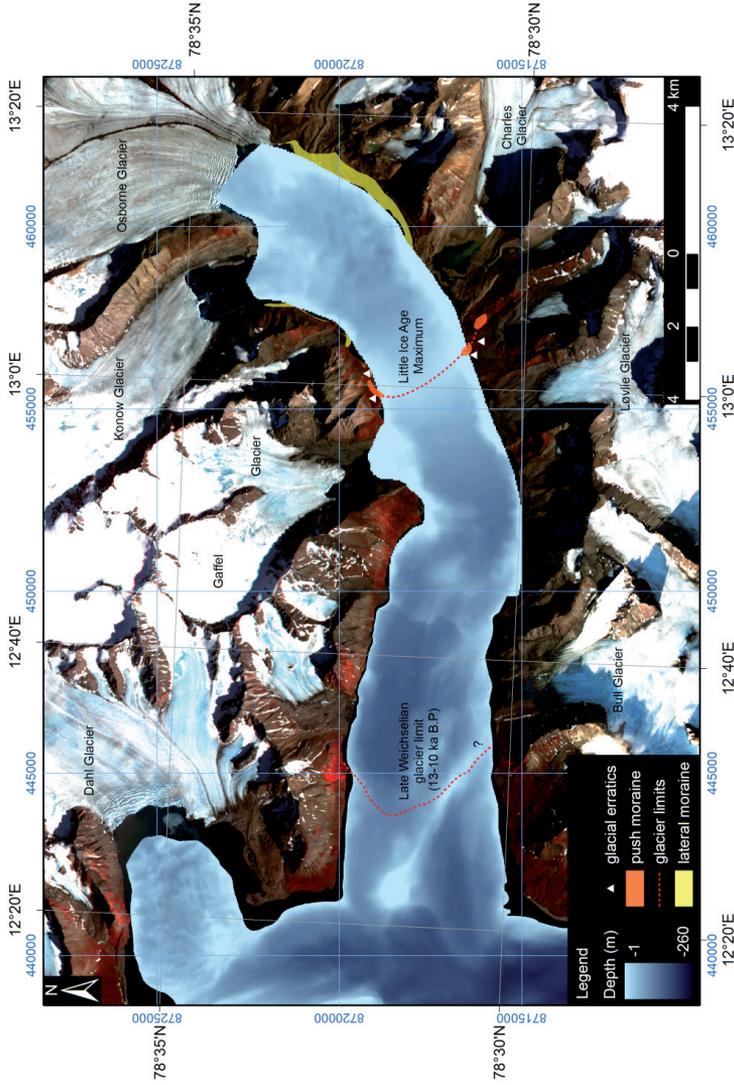


Fig. 3. Bathymetry map of the St. Jonsfjorden area and glacier limits connected to the Konow/Osborne Glacier during the Little Ice Age (LIA) and Late Weichselian (13–10 ka B.P.) (based on the bathymetric data reproduced with the permission of the Norwegian Hydrographic Service, permission no. G641)

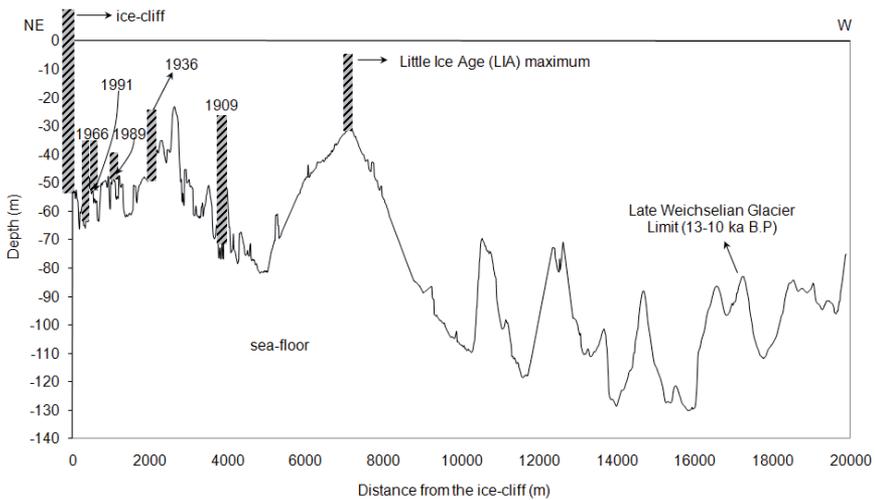


Fig. 4. Bathymetric transect along St. Jonsfjorden axes. The past positions of the tidewater ice-front are derived from historical maps and aerial photographs

appear to result from soft-sediment deformation at the base of fast-flowing ice streams draining large ice masses (Tulaczyk et al. 2001; Dowdeswell et al. 2004; Ó Cofaigh et al. 2005; Ottesen et al. 2007).

In that zone the relief of the bottom demonstrates the features which seem to be similar to flutings or flutings with initiating boulder (Christoffersen et al. 2005; Larsen et al. 2006). These forms were the basis for the delimitation of the extension of the Konow-Osborne Glacier in Late Weichselian (13–10 ka B.P.). The glacier terminated 2 to 4 km from the fjord's outlet leaving about 15 km² of ice-free area. Thus, in relation to the maximum extension from the LIA, the glacier advanced further by about 12 km.

Summary

There are many studies suggesting that the Late Weichselian ice sheet reached the continental shelf edge west and north of Svalbard (Svendsen et al. 1992, 1996, 2004; Andersen et al. 1996; Landvik et al. 1998; Mangerud et al. 2002; Ottessen et al. 2007). However, our study is closer to the hypothesis that glacial ice filled the Isfjorden and Kongsfjordrenna cross-shelf

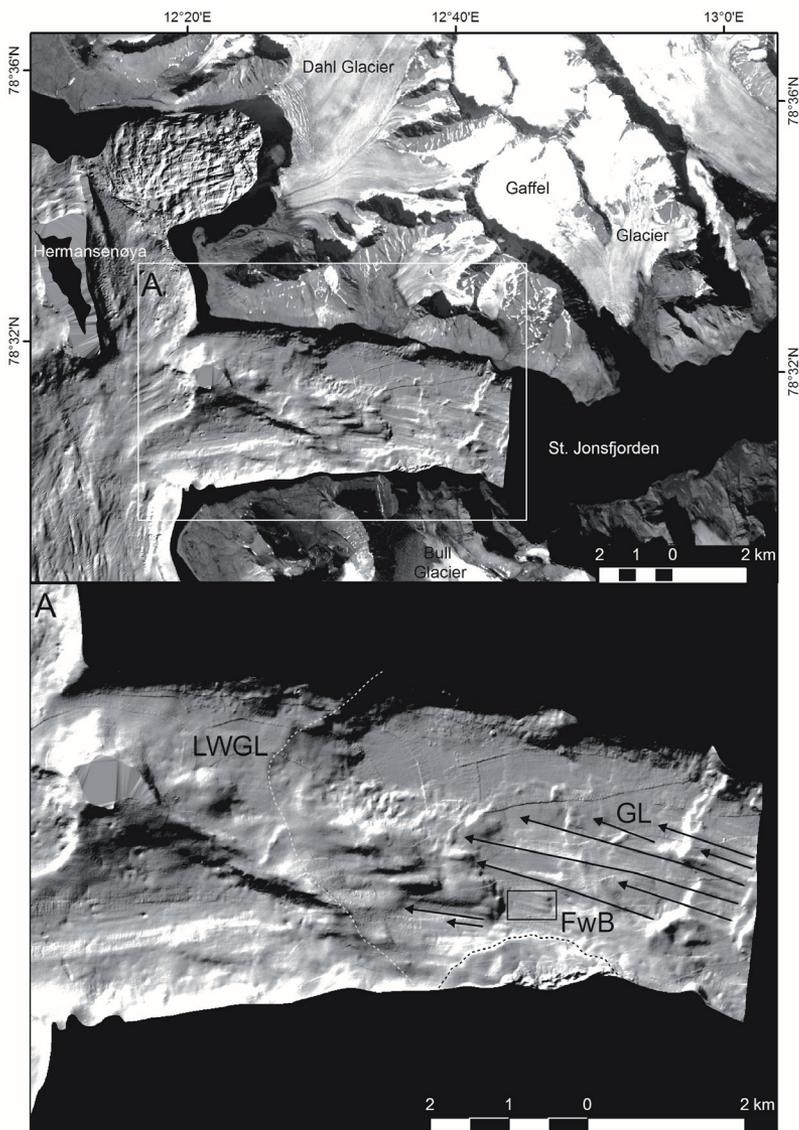


Fig. 5. Shaded-relief image of the St. Jonsfjorden area – the mouth part of the fjord. The image shows glacial lineations (GL) (black arrows) generally orientated south-east to north-west. Between lineations the fluting with initiating boulder (FwB) was found on the sea-floor. White dotted line indicates the Late Weichselian Limit (LWGL) of the Konow/Osborne Glacier. At the southern part of the fjord a black dotted line shows the Little Ice Age (LIA) terminal ridge of the Bull Glacier (reproduced with the permission from the Norwegian Hydrographic Service, permission no. G641)

troughs as low gradient outlet glaciers while parts of the present coastal areas of Prince Karls Forland and east coast of Forlandsundet were ice-free (Andersson et al. 1999, 2000; Houmark-Nielsen and Funder 1999). This hypothesis has been accepted by Landvik et al. (2005) as one of a number which are possible. We suggest that the presence of glacially undistributed pre-Late Weichselian raised beaches in the Kafføyra and St. Jonsfjorden regions indicates that the landforms were not covered by glaciers during the LGM (Last Glacial Maximum) (Forman 1989, 1990; Niewiarowski et al. 1993; Evans and Rea 2005).

Based on the submarine landforms we suggest that during the Late Weichselian (13–10 ka B.P.) Dahl Glacier did not cover the entire area of the contemporary Hermansenøya. The glacier advanced only to the northern part of the island. On the basis of the shaded relief images it was concluded that 13–10 ka B.P. the Konow-Osborne Glacier terminated 2 to 4 km from the fjord's outlet leaving about 15 km² of ice-free area. In the mouth area of St. Jonsfjorden and in the central part of Forlandsundet there is no evidence of glacial relief, which may indicate the presence of ice-sheet.

Acknowledgements

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