The Last Glacial Maximum, Deglaciation and Post-Glacial History of Forlandsundet, an Inter-Ice Stream Glaciated Margin, Western Svalbard

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Late Weichselian glacial history of Forlandsundet, western Svalbard: an inter-ice stream setting

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Abstract

The Last Glacial Maximum (LGM) and post-glacial Quaternary history of Forlandsundet, the strait between western Spitsbergen and Prins Karls Forland, is enigmatic. Previous terrestrial field studies report contradicting evidence for an ice sheet either overriding the entire strait or completely absent during the LGM. Here we present a multi-proxy investigation of marine sediments, high-resolution bathymetric data and aerial imagery from Forlandsundet. We reveal glacial till present at 15 cal. ka BP and geomorphological landforms characteristic to an inter-ice-stream glaciated margin. This new evidence implies that the Forlandsundet region was fully glaciated during the LGM. This glaciation was followed by a stepwise retreat of glacial ice during the Bølling-Allerød (14.7 – 12.7 cal. ka BP) and Younger Dryas (12.7 – 11.7 cal. ka BP). The Holocene record from the marine sediments is incomplete, with a hiatus from approximately 11.8 to 7.4 cal. ka BP, interpreted as an erosive event. By the mid-Holocene (7.4 cal. ka BP), more temperate, Atlantic conditions based on the benthic foraminiferal assemblages prevailed, and are followed by gradual cooling into the late Holocene (<4 cal. ka BP). This study provides new data to resolve the LGM extent of the Svalbard-Barents Sea Ice Sheet in the Forlandsundet region and sheds light on the deglacial ice dynamics in a palaeo-inter-ice-stream area driven by the inflow of warm Atlantic water.

Key words: Last Glacial Maximum, Forlandsundet, Svalbard, deglaciation, inter-ice-stream, submarine landforms, foraminifera
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**Introduction**

The growth and decay of large ice sheets during full glacial periods leaves imprints of ice flow and extent on the landscape. In addition, the ice masses erode a vast amount of material and discharge it at their margins. Understanding the past dimensions and dynamics of glacier ice on Svalbard provides boundary conditions to model future changes of modern marine-based ice sheets, as well as iceberg and meltwater production [1]. Thus, there are numerous investigations on the geomorphological and sedimentological evidence of the maximum extent of the Svalbard Barents-Sea Ice Sheet (SBSIS) during the LGM and its decay on the western Svalbard margin [2–4]. Notably, Forlandsundet, the strait between Isfjorden and Kongsfjorden, confined by Prins Karls Forland to the west and the island of Spitsbergen in the east (Fig. 1), has been subject to extensive debate with regard to its glacial history [5–7]. Forlandsundet was an inter-ice-stream setting with slower ice flow, while Isfjorden and Kongsfjorden accommodated major ice streams that drained substantial volumes of the SBSIS after initiation about 21 cal. ka BP [2, 8]. Despite debate about the unresolved glacial history of this area, the marine sedimentary record of southern Forlandsundet has until now remained unstudied.

**Regional Setting**

The Forlandsundet Graben is a basin of Tertiary sediment in the West-Spitsbergen fold-and-thrust belt. It was originally formed during regional dextral transpressional tectonic regimes in the Eocene to Early Oligocene [9]. The study area centers around 12°18'51"E 78°22'28"N, including central and southern Forlandsundet, outer St. Jonsfjorden, Dahlbrebukta, Eidembukta and Selvågen Bay, encompassing an area of about 1100 km² (Fig. 1). The SBSIS reached the western Svalbard shelf edge three times during the Weichselian since marine isotope stage (MIS) 5d [10], most recently at about 23-24 cal. ka BP during MIS 2 [11–13]. During this advance, the ice sheet remained at the maximum extent for only 3-5 ka [12], before retreating by 16.5-17.4 cal. ka BP from the outer shelf [14–16]. Grounding zone wedges and recessional moraines indicate a stepwise retreat from the shelf west of Isfjorden [2, 6], between approximately 17.4 and 11 cal. ka BP [15]. Svendsen et al. [15] have identified an Older Dryas readvance on the shelf south-west of Prins Karls Forland at 14 cal. ka BP from mollusc shells in glacial till that corresponds to the grounding-zone wedge mapped by Ottesen et al. [2]. Older radiocarbon ages in glacimarine mud in the retreat zone and in the mouth of Isfjorden complicate this chronology but could be explained by iceberg ploughing. Forwick and Vorren [4] have suggested that glaciers had retreated into the innermost Isfjorden by 11.2 cal. ka BP. The Younger Dryas manifested in glacial readvances of major fjord glaciers and/or multi-annual shorefast sea ice, evidenced by the reduction in ice rafted debris [4, 17]. The smaller
extent of glacier readvance on western Svalbard during the Younger Dryas compared to the Little Ice Age might be attributed to the prevailing easterly winds, starving the glaciers of precipitation [18].

The extent of land-based ice in the Forlandsundet area during the LGM is highly debated, ranging from a complete absence of ice [19–21] to full grounded ice cover flowing to the west during the Late Weichselian [22]. The ice-free enclave hypothesis is based on the preservation of pre-LGM shorelines, whalebones and minimal geomorphological evidence of glaciation at Poolepynten [19, 21]. Forman [19] has suggested that the Late Weichselian ice sheet terminated 2–4 km east of the mouth of St Jonsfjorden and had retreated to >5 km from the fjord mouth by 11.5 cal. ka BP. This date is based on a recalibrated age of 10.3 cal. ka BP (9525 ±90 yr BP) derived from Mya truncata shells in sub-littoral sediments on the northern shore of St Jonsfjorden (recalibration is based on Stuiver and Reimer [23]). This deglaciation age is supported by the discovery of the thermophilous mollusc Modiolus modiolus, that migrated rapidly northwards following ice retreat in St. Jonsfjorden [24]. Supporters of maximum ice cover attribute the preservation of sediments from earlier than 36 ka to a possibly short duration of ice-flow [6], or presence of cold-based ice [6, 25]. Based on glacially striated bedrock and glacial erratics on northern Prins Karls Forland, Ingólfsson and Landvik [5] proposed a westward flow during maximum glaciation and switching to northward flow after the break-up of the Isfjorden and Kongsfjorden ice stream [7].

Based on low ice rafted debris (IRD) flux in Isfjorden as well as foraminifera assemblages in fjords and on the Svalbard margin, the early Holocene (from 11 cal. ka BP) has been described as a climatically warm period, with increasing influx of Atlantic water [4, 26–28]. This was followed by abrupt cooling at 8.8 cal. ka BP on the continental margin and prolonged cooling 8-4 cal. ka BP marked by rising numbers of the Arctic species Elphidium clavatum in fjord records [29]. Increases in IRD flux and low fluxes of benthic foraminifera in western Spitsbergen fjords indicate a phase of further cooling after 4 cal. ka BP [28, 29].

This investigation aims to elucidate the LGM ice-sheet extent, dynamics and the timing of retreat of the SBSIS in southern Forlandsundet by combining evidence from multibeam bathymetry, aerial photography and a marine sediment core.

**Methods**

**Geomorphology**

Multibeam bathymetry data was collected by the Norwegian Hydrographic Service between 1999 and 2004, using an EM1002 multi-beam echo sounder. Digital elevation models (DEM) with a 10 m isometric grid size and bathymetry profiles were created using ESRI ArcMap 10.2 and QPS Fledermaus software. Colour coded bathymetry maps and shaded
relief images of DEMs were used to describe and interpret submarine landforms in the central and southern Forlandsundet area. Additionally, orthorectified aerial images of the study area obtained by the Norwegian Polar Institute (NPI) in 2009, were analysed for glacial landforms along the coastline between the glaciers of Dahlbreen and Eidembreen (Fig. 1 & 2).

**Sedimentology**

In June 2013, a 3.5 m gravity core HH13-04-GC was retrieved by RV Helmer Hanssen at 78°23.422’N, 12°22.453’E at a water depth of 145 m from flat (~0.3°) seabed on the north-eastern part of the bathymetric rise that divides southern Forlandsundet into a southern and northern basin (see Fig. 1). It was split, and the working half was studied as part of the Arctic Marine Geology course at the University Centre in Svalbard (UNIS) in 2014. The archive half was stored at 4°C at UNIS and shipped to the Scottish Association for Marine Science, where it was investigated in 2015-2016. The core was in good condition, even though oxidation over the one-year storage period in the cold room since splitting has probably affected the colouration and water-saturation of the sediments.

**Logging of visual and physical properties**

The sediment core was logged with a Geotek Multi-Sensor Core Logger (MSCL), providing continuous (1 cm) down-core measurements of magnetic susceptibility, p-wave velocity and bulk density. Lithological units were distinguished based on sediment colour [30], texture, structures, as well as the presence of bioturbation and clasts. Shear strength was determined with a Geonor fall cone apparatus at 2 cm intervals.

**Grain size analysis**

Approximately 1 g of sediment was subsampled at 5 cm intervals and dissolved in 5 ml of sodium hexametaphosphate and sodium carbonate solution diluted with 15 ml of DI water. Grain size for the <1 mm fraction was determined as percentage volume using a Coulter Counter laser diffraction particle size analyser set at polarized intensity differential scattering to better resolve the clay fraction. The >1 mm fraction, which is prone to block the channels of the particle size analyser was excluded and measured as percentage of total dry weight at 10 cm intervals and interpreted as IRD.

**Micropalaeontology and chronology**

The core was subsampled for foraminifera analysis at 20 cm intervals and additional subsamples were taken to increase the resolution to 10 cm intervals at core depths between 130 and 170 cm. The subsamples were freeze-dried for 72 hours and weighed, before sieving through 63 µm, 125 µm and 1 mm meshes. In the 125 µm – 1 mm fraction of each subsample at least 300 or all benthic foraminifera present were counted and identified to species level under an Olympus SZ60 light microscope, following the classification of Austin [31], with some recent revision of the elphidiid taxonomy following
Darling et al. [32]. Unbiased splits were obtained from very abundant subsamples (with >600 tests per sample), and the entire split was counted. Samples were split by weighing the entire sample, spreading the sediment in a figure-of-eight and subsampling the centre section to include the entire spectrum of grain sizes. The concentration of benthic foraminifera is presented as flux values, derived from MSCL bulk density and linear sedimentation rate calculations.

At 130, 150 and 270 cm below sea floor (bsf), foraminifera subsamples were picked and submitted to the $^{14}$Chrono Centre of Queens University Belfast for radiocarbon dating. The 150 cm sample comprised monospecific Nonionella labradorica, while the 130 and 270 cm samples consisted of mixed benthic foraminifera because there were insufficient specimens of a single species present (see Table 1). The radiocarbon dates were converted to calibrated kiloyears before present (cal. ka BP) in Calib7.1 (http://calib.org/) [23], with a regional reservoir age offset $\Delta R = 100 \pm 39$ added to the Marine 13 calibration curve’s inherent correction of 405 years [33], based on samples from the QUB marine reservoir correction database (http://calib.org/marine, [34, 35]). An age-depth model was created using Bacon R [36], assuming a modern core top age to calculate linear sedimentation rates. The chosen $\Delta R$ corrects the apparent ages due to carbon exchange and reservoir effect of the dating material based on Holocene oceanographic conditions, which likely underestimate the regional offset during deglaciation.

Results & Interpretations

Geomorphology

The geomorphology of Forlandsundet consists of bedrock features as well as signatures of subglacial erosion and glaciomarine depositional processes. In the following section various geomorphological features are described, and landform assemblages are interpreted in terms of sedimentary processes and stratigraphic relationships. Fig. 1 shows the distribution of these landforms.

Feature 1: Overprinted lineations

Lineations overprinted by transverse ridges (described below) are found in Selvågen Bay and Dahlbrebukta as well as St. Jonsfjorden. They are typically 500-1000 m long and up to 50 m wide with a relief of ~5 m (Fig. 3a and Fig. 3c).

The lineations are perpendicular to the modern glacier margin in Dahlbrebukta and are parallel to the fjord axis in St Jonsfjorden. These lineations are interpreted as mega scale glacial lineations (MSGLs) formed by fast flowing, possibly surging glacier ice [e.g.37].
**Feature 2: Elongate streamlined features**

Four submarine hills, elongate in shape and parallel to the fjord axis are evident in St Jonsfjorden, about 2.5 km north of Bullbreen (Fig. 3 b). These bedforms are about 400 m in length, have steep eastern slopes and taper off on the western sides. The eastern ends are 50-80 m wide, but the features thin markedly towards the lee end. These landforms are interpreted as ‘crag and tails’ or drumlins.

**Feature 3: Subparallel linear depressions**

In the centre of Forlandsundet, muted, linear depressions are concentrated in a field about 5-6 km west of Hermansøya (Fig. 3 e). These depressions are subparallel to one another, oriented approximately south to north. They are between 50-200 m wide, 300-1000 m long and typically ≪3 m deep. Such elongated depressions are also present in the deeper, southern basin of the Forlandsundet strait where it opens into the Isfjorden Trough. These bedforms are interpreted as sub-glacial lineations subsequently buried by sediment.

**Feature 4: Steeply sloping longitudinal ridges**

West of Hermansøya, a large streamlined feature stretches northwest to southeast, with a height of up to 60 m, width of about 900 m, length of 8 km and slopes of up to 25° on its sides (Fig. 1). South of the fjord mouth, large streamlined features appear to run approximately north to south (Fig. 3 f). These features are 500-3000 m long, up to 400 m wide and with variable morphology, sloping up to 40° on their eastern and western flanks. The steep slopes and rugged morphology of these ridges indicate that they are glacially scoured bedrock remnants, similar to bedrock ridges observed in Lomsfjorden [38]. The southernmost ridges peter and widen into a bathymetric rise on their lee side, indicating higher sediment accumulation akin to crag-and-tails. The glacial erosion is more pronounced in the metamorphosed Palaeozoic folded rocks that have undergone transverse compression [39]. This interpretation is supported by the shallow (10-20m bsf) acoustic basement revealed by seismic lines in the east of Forlandsundet [see Fig. 4 of 15].

**Feature 5: Arcuate transverse ridges**

Arcuate transverse ridges, several hundred meters wide and with a vertical relief of 15-30 m are found transverse to modern ice flow direction on the seabed as well as on land (Fig. 1, Fig 2 c & 2 d). In Dahlbrebukta, a 20 m high ridge spans the bay approximately 5 km from the modern glacier margin (Fig. 1). Because of its size and ice-distal position, this is interpreted as a terminal moraine of a recent glacier advance. A second arcuate ridge runs approximately east to west on the south shore of the bay (Fig. 1).

A 14 km long ridge stretches north to south about 3000 m from the 2009 glacier front of Eidembreen, constrained by mountains either side (Fig. 3 d); the aerial imagery shows about two-thirds of this ridge, which peters out towards the bay, where the remainder may have been eroded by glacio-fluvial processes.
On the St Jonsfjorden seabed, 2.3 km north of the present Bullbreen margin, a 2.8 km long arched ridge runs parallel to the Bullbreen ice flow direction. Near the north shore of St. Jonsfjorden, aerial images reveal a segmented ridge across the valley ~800 m south of the modern limit of Ankerbreen (Fig 1). The segmentation is postulated to be a result of glacio-fluvial erosion, and the ridges are interpreted as terminal moraines marking the LIA extent of Bullbreen and Ankerbreen respectively.

**Feature 6: Superimposed transverse ridges**

Transverse ridges with a relief of c. 5 m, locally as high as 12 m, span across Selvågen Bay and Dahlbrebukta (Fig. 1 and Fig. 3 a). In St Jonsfjorden, similar closely spaced ridges run perpendicular to the fjord axis but appear partly buried in an infilled basin (Fig. 3b & 2c). The ridges are steeper on the stoss than on the lee side and are superimposed onto the lineations described above (Feature 1). In Dalhbrebukta, 46 individual ridges were identified from the bathymetric data. There is a change in the ridge orientation, from approximately northerly (~0°) trending ridges on the ice-distal side of the bay to north-westerly (~350°) about 1500 m from the modern glacier margin (Fig. 3 a). These ridges are interpreted as De Geer moraines formed during an episodic retreat associated with periods of sea ice cover suppressing calving at the ice margin and instead causing the glacier to push sediment during small readvances [40]. The irregularly arcuate shape of the ridges, their height as well as the asymmetry of the stoss and lee sides support the interpretation of De Geer moraines over crevasse squeezed ridges (CSR), but in a surge type setting the latter cannot be entirely excluded. While no surge has been reported on Dahlbreen, it has been identified as a potential surge glacier based on smaller CSR in the glacier foreland [41].

**Feature 7: E-W trending bathymetric rise**

Between Eidembreen and Forlandsletta, an elevated area with a width of about 4 km extends for 12 km across Forlandsundet, dividing it into a southern and northern basin (Fig. 1). This elevation has a slope of 1.5° on its northern flank and 1° on the southern one, and has a relatively flat top measuring 40 km² at a water depth of 140-170 m. The eastern half of this bathymetric high is shallower and wider, forming a transition into the longitudinal ridges (Feature 4). Based on its morphology and the association with the longitudinal ridges, we suggest that the eastern part was subject to higher sediment accumulation rates than further west. While this feature most likely reflects the morphology of the basement rock, it is postulated that this bedrock high facilitated the formation of a grounding-zone wedge by stabilizing the ice margin during the retreat of the SBSIS [42, 43].
Chronological Relationships of Landform Assemblages

The proximal positions of arcuate transverse ridges to modern glacier fronts suggest that they mark the terminal extent of the most recent ice activity. While the E-W trending ridge on the southern shore of Dahlbrebukta is subparallel to modern ice flow Dahlbreen, it is interpreted as a terminal moraine of a former cirque glacier on the N-NW flank of Ankerfjella, which has since melted. Farnsworth et al. [24] have identified the neoglacial (i.e. Little Ice Age) maximum extent of Osornebreen at about 8.5 km from the modern glacier margin, now terminating at the head of St Jonsfjorden. The advance of Dahlbreen to 5 km (Feature 5, Fig 2 A) from its modern terminus is thus possibly also of neoglacial age but requires verification. On the basis of this complex assemblage of related glacial landforms including moraines and MSGLs in Dahlbrebukta and by analogy with similar landform assemblages in Svalbard fjords, the De Geer moraines probably formed during stepwise (potentially annual) retreat following an advance of a fast-flowing glacier [see 37, 40].

The streamlined and elongated morphology of Features 2-4 in the deep basins of Forlandsundet (Fig. 1 & Fig. 3, e-f) suggests their formation under flowing ice [37]. Therefore, we interpret the features in Forlandsundet to have formed as ice occupied the area, probably during the transitional phase following the initial retreat of the SBSIS from its LGM extent and during the breakup of ice-streams [see 5]. The smaller lineations in St. Jonsfjorden (Fig. 3 c) formed at a later stage of ice retreat and potential readvance, as they are confined to the topography of this tributary fjord and terminate at the retreat moraines in the area [40].

Sedimentology

Unit 1 – clayey silt (0-140 cm)

This unit consists of clayey silt (silt content of >60%), dark olive grey in colour (5Y 3/2, [25]) with occasional olive yellow mottling (5Y 6/6) (Fig. 4 A). At 30 cm bsf, there is a 3 cm thick very dark grey layer (2.5Y 3/1) that appears slightly coarser-grained. A 3 mm shell fragment was found at 40 cm bsf and layers of IRD were identified at 40, 72-83, and 136 cm bsf, which correspond to an increase in percentage weight of the >1 mm fraction (Fig. 4 F). Magnetic susceptibility, shear strength and bulk density, plotted against core depth in Fig. 4 B-D confirm the distinct facies of Unit 1. Within this unit, magnetic susceptibilities are relatively stable between 20 and 39 SI from the core top to 120 cm bsf, before increasing towards the lower unit boundary. Bulk density values for Unit 1 lie between 2.0 and 2.5 g cm$^3$ and shear strength varies between 27 and 56 kPa with a single peak at 30-32 cm bsf coinciding with the above described coarser layer, which may account for the coarse texture through compaction and dewatering.
**Transition – clayey silt to laminated silty clay (140-147 cm)**

At 140-147 cm bsf a convoluted transition occurs, between coarser sediments and laminated silty clay. A >1 cm dropstone at 147 cm bsf establishes a sharp contact between Unit 1 and Unit 2 near the core liner. However, between 140 and 147 cm bsf, coarser sediments of Unit 1 inter-finger with laminated silty clay, forming a convoluted transition across two-thirds of the core width. In this transition zone, magnetic susceptibilities increase steeply to 62 SI by 147 cm bsf. This is interpreted as an erosional boundary based on the high energy that would be necessary to create such a sharp yet convoluted contact.

**Unit 2 – laminated silty clay (147-260 cm bsf)**

Unit 2 consists of brown, finely laminated silty clay (2.5Y 3/2) from the convoluted transition at 147 cm bsf with a gradational boundary to massive mud at about 260 cm bsf. Magnetic susceptibilities (Fig. 4B) are consistently between 33 and 47 SI down to 230 cm bsf (with the exception of two outliers at 208-209 cm bsf). From a dip at 25 SI at 231 cm bsf, values increase steadily towards the lower boundary of Unit 2; there is no notable change in grain size over this interval. Shear strength values are between 7.5 and 30 kPa from 150 to 266 cm bsf, and bulk density varies between 2.4 and 2.8 g cm$^{-3}$ decreasing downcore to 2.0 g cm$^{-3}$ at 230 cm bsf. Unit 2 has a low sand content (<5%) and the clay fraction increases with core-depth, peaking at 230 cm bsf, which correlates to low values in bulk density (Fig. 4 D). At 240 cm bsf, a well preserved internal shell of an opisthobranch mollusc was found, identified to genus *Cylichna*, most likely *C. occulta*.

**Unit 3 – massive sily clay with dropstones and layers of diamicton (260-313 cm bsf)**

Between 260 and 313 cm bsf, there is an increasing number of clasts up to 2.5 cm in diameter and two distinct layers of dark grey diamicton (5Y 4/1) inter-finger with the silty clay at 283-293 cm bsf and at 294-301 cm bsf. The sediment becomes significantly coarser within Unit 3, with the >1 mm fraction making up 10-30% of the subsample weight (Fig. 4 F). Shear strengths increase to values of 17 to 71 kPa (Fig. 4 C), and magnetic susceptibilities vary between 19 and 68 SI (Fig. 4 B). Bulk density measurements also exhibit large variations, which we interpret as possibly related to dewatering.

**Unit 4 – massive diamicton (313-342 cm bsf)**

At 313 cm bsf, there is a sharp contact from grey silty clay to a dark grey (5Y 4/1) matrix-supported massive diamicton with clasts up to several centimetres in size. The >1 mm fraction represents >40% of subsample weight, and diffraction particle size analysis indicates that the clay fraction decreased to <30%. P-wave velocities decreases to less than 2000 ms$^{-1}$ and shear strength increases to values of >100 kPa.
**Biosstratigraphy**

**Micropalaeontology**

The micropalaeontological description and palaeoenvironmental analysis focuses on the calcifying benthic foraminifera that dominated the sediments, agglutinating and planktonic specimens were rare. Fig. 5 shows the relative concentration of the most abundant benthic foraminifera in the sediment core. The foraminiferal assemblage of Unit 1 is dominated by *Cibicides lobatulus*, contributing 45-70% of the counted individuals in this unit. Modern species assemblages dominated by the cosmopolitan, eurythermal species *C. lobatulus* are found in the coarse sediments of outer Isfjorden [44]. *E. clavatum* is the second most abundant species, accounting for 10-20% of the samples. *Buccella spp.* and *Nonionella labradorica* each constitute about 8% of all individual foraminifera in subsamples of Unit 1. The numbers of *C. lobatulus* drop sharply with the transition to Unit 2, while *N. labradorica* peaks at 40% with a subdominant abundance of *Cassidulina reniforme* in this transition at 150 cm bsf. *C. reniforme* increases in numbers from 110 cm bsf, and dominates the assemblages in Units 2 and 3, occurring with *Elphidium clavatum* and the less abundant species *Islandiella helenae*.

The 230 cm bsf subsample and all subsamples of Unit 4 were completely barren with respect to foraminifera. The increase in clay to >50% and barren foraminifera subsample at 230 cm most likely relates to a localized burial event with much higher sedimentation rates.

The flux of benthic foraminifera peaks at 130 and 140 cm bsf (Fig. 5) and is markedly lower in Units 2 and 3 compared to Unit 1. At 250 cms bsf, foraminifera concentrations almost reach the levels of Unit 1, coinciding with a peak in *E. clavatum* and *N. labradorica*. A similar species assemblage, albeit with an even higher relative concentration of *E. clavatum* and *N. labradorica* compared to *C. reniforme*, has also been described for the Younger Dryas at the mouth of Kongsfjorden [28].

**14C Chronology**

Radiocarbon and calibrated ages are listed in Table 1 and the computed age-depth model is presented in Fig. 5. Unit 1 consists of Holocene sediments up to 7.4 cal. ka BP in age (95% CI: 7009-8211). The age difference of 5 cal. ka between the 130 and 150 cm bsf radiocarbon samples suggests an age hiatus (possibly as long as 4.5 ka) at the boundary from Unit 1 to Unit 2. This supports the assumption of the presence of an erosional boundary, identified during visual logging of the sediment core.

The available age-control suggests that Unit 2 was deposited from the end of the Bølling–Allerød interstadial (14.7 – 12.7 cal. ka BP) to the Younger Dryas stadial (12.7 – 11.7 cal. ka BP). Unit 3 dates back to approximately 14.5 cal. ka BP, extrapolated using linear sedimentation rates from the radiocarbon date at 270 cm bsf to 310cm bsf. While this limits
accuracy due to insufficient foraminifera for dating below 270 cm bsf, the available dates suggest that the massive
diamicton of Unit 4 was deposited during early deglaciation, approximately 15 cal. ka BP and that Forlandsundet was
ice-free by at least 14.2 cal. ka BP.

Interpretation

Unit 1 is interpreted as poorly sorted glacimarine mud, deposited under the influence of temperate Atlantic water. The
presence of *C. lobatulus* indicate strong bottom currents [45], and ample food supply is partly evidenced by the high
concentration of foraminifera tests per gram of sediment. This could have resulted from a amplified inflow of Atlantic
water, which appears to decrease towards the top of the core implied by the gradually decreasing productivity of benthic
foraminifera. The inflow of warmer Atlantic water is also supported by the discovery of thermophilous mollusc
*Modiolus modiolus* at 10 cal. ka BP in the inner part of St. Jonsfjorden [24].

The hiatus of approximately 4.5 ka at the convoluted boundary 136-145 cm bsf may be related to erosive event such as
a submarine mass movement or a period of non-deposition and bottom-current erosion. A similar hiatus was reported
from sediment core HH12-956-GCMF taken at the mouth of St. Jonsfjorden (Fig. 1, [46]) and whilst there is no
evidence of a localized mass-movement such as slide scars at the core site, this supports the interpretation that this
hiatus may have been a large-scale erosional event or extended period of non-deposition.

In contrast, a low-energy depositional environment, possibly under perennial ice cover is proposed for Unit 2, with
suspending settling from meltwater plumes causing the formation of fine lamination [see 47]. At the top of Unit 2, the
peak in *N. labradorica* and an increase in *C. reniforme* is accompanied by decreasing abundance of *E. clavatum*. This is
similar to the Holocene transition period observed in Kongsfjorden (11.5-10.6 ka) and interpreted as reflecting the
proximity of the Arctic Front and an increase in Atlantic water that caused a rapid glacial retreat within fjords [28]. High
relative abundance of *C. reniforme* is typically associated with proglacial low-salinity environments in Svalbard’s fjords
[44], and its increase down-core through Units 2 and 3 reflects the proximity of a glacier terminus.

Unit 3 is thought to be an ice-proximal deposit arising from rapid retreat of the grounding line that can produce both ice
rafted diamicton as well as dropstone mud commonly associated with more ice-distal glacimarine settings [see 48]. The
high variation in bulk density values between Units 3 and 4 is attributed to the contribution of different lithologies through
glacial transport. High shear strength values partly reflect dewatering of the core, especially where sediment is coarser,
but values of >100 kPa in Unit 4 may also be attributed to compaction by an overriding glacier [49]. Unit 4 is thus
interpreted as a subglacial till deposited before or during retreat of the last ice sheet that covered Forlandsundet.
Based on the sediment record and geomorphological evidence from Forlandsundet, we suggest that the SBSIS occupied this area of western Spitsbergen during the LGM. Given the complex assemblages of glacial landforms and an interpreted depositional deglaciation sequence in core HH13-04-GC, which includes subglacial landforms and tills, an ice-free enclave would be highly unlikely [contra 19–21].

Evidence for westward maximum ice flow during the LGM is lacking in the south-western part of Forlandsundet [cf. 7], as one would expect east-west trending lineations. This suggests that during the maximum extent of the late Weichselian glacial ice was cold-based in the southern Forlandsundet [22, 25], and left only local imprints on the submarine landscape during short and likely late periods of thawed bed conditions [22]. The geological record is skewed towards younger deglacial events, which may have also overprinted any signatures of westward flow during the LGM that have a low preservation potential in inter-fjord areas [22]. Interpreting the geomorphological evidence in the study area, we suggest a conceptual ice sheet behaviour model for southern Forlandsundet as a tributary to the Isfjorden ice stream during deglaciation (Fig. 6a), a period of time when ice flow was controlled topographically [22]. This implies that Prins Karls Forland acted as an ice divide during deglaciation, with northern Forlandsundet as a tributary to Kongsfjorden [20], and southern Forlandsundet draining into the Isfjorden cross shelf trough (CST). The ice sheet surface is assumed at 500 m above sea level (a.s.l.) based on glacial erratics and $^{10}$Be exposure ages at >470 m a.s.l. in northern Forlandsundet [7].

The available evidence limits potentially ice-free areas in the Southern Forlandsundet to mountain tops (nunataks), which requires verification in the St Jonsfjorden region (Fig. 6a).

The radiocarbon date for the ice-proximal sediments from a core depth of 270 cm in Forlandsundet of approximately 14.2 cal. ka BP corresponds to the SBSIS retreat through the Isfjorden CST south of Forlandsundet [15]. However, the 14 cal. ka BP readvance of the SBSIS during the Older Dryas based on the observations of a moraine south-west of Prins Karls Forland by Svendsen et al. [15] is not evident in the depositional record from the sediment core from Forlandsundet. Here, the seabed geomorphological and sedimentological evidence suggests that the ice sheet may have experienced an Older Dryas still-stand during retreat near the core site and formed a grounding line while pinned at a bathymetric high, or readvanced after an earlier retreat north of this feature (Feature 7, Fig. 6b). The dominance of dropstone muds and presence of benthic foraminifera is clear evidence that the glacial readvance in Isfjorden did not extend to the core site in Forlandsundet. An ice-sheet readvance south-west of Prins-Karls Forland could have been confined locally to the Isfjorden CST, similar to the most recent readvance on the Labrador shelf [50].
The laminated sediments, high clay and low IRD content of Unit 2, interpreted as ice-proximal meltwater plumes deposited during the Younger Dryas could indicate a floating ice shelf or sea ice that suppressed iceberg calving and lead to suspension settling [47] as observed in Isfjorden [4]. The transverse moraines in St Jonsfjorden, likely formed during retreat indicating that the ice retreat was stepwise, following an Older Dryas stillstand. A Younger Dryas retreat position is thus postulated east of the HH12-956-GCFM core site that was finally deglaciated by 12.8 cal. ka BP (Fig. 1 and Fig. 6 c. [46]). The change in structure, grain size and foraminifera composition from the bottom to the top of Unit 3 also suggest a shift from a proglacial environment to an ice-distal setting. The dominance of Cassidulina reniforme and presence of Islandiella helenae indicate coastal water salinities higher than those preferred by Elphidium clavatum [51], and as such points to an increasing influence of Atlantic water in a proglacial environment. Inflow of warm, saline Atlantic water was an important factor in the decay of the marine terminating ice sheet, as also evidenced by the presence of thermophilous molluscs following the deglaciation of inner St Jonsfjorden [24]. The higher abundance of *E. clavatum* and decreasing values of *C. reniforme* towards the top of Unit 3 and at the bottom of Unit 2 may reflect cooling and lowered salinity due to a reduction in the inflow of Atlantic water during the Younger Dryas [46], as also observed in Kongsfjorden [23], providing further evidence that the ice retreat occurred in a stepwise manner and was at least partly driven by oceanographic conditions. At the top of Unit 2, the peak in *N. labradorica* may indicate the proximity of the Polar Front and in the transition towards the Early Holocene climatic optimum; a similar peak at the end of the Younger Dryas is described for Hinlopen, Kongsfjordrenna and Bellsund [28].

The hiatus between Unit 1 and 2 is also indicated by Bunin’s [46] radiocarbon dates from HH12-956-GCFM at the mouth of St Jonsfjorden, and the lack of slide scars at either core site supports the hypothesis of a more widespread erosional event affecting the entire southern Forlandsundet and outer St Jonsfjorden basin. This unconformity could result from post-glacial slope failures and turbidite erosion from submarine mass-movements, as observed locally in Hadangerfjorden [52], or at a larger scale like several tsunami deposits identified along the Norwegian and East Greenland coast as a result of the Storegga slide [53–56]. Peacock et al. [57] attributed a 2000-year unconformity on the Scottish shelf to post-glacial bottom current erosion — another potential cause the hiatus in Forlandsundet, which warrants further investigation.

The trend of a late Holocene cooling (<4 cal. ka BP) identified along the west coast of Svalbard [e.g. 51] is supported in this study by decreasing productivity towards the top of the sediment core, but conditions appear to have been more favourable in the mid Holocene, where productivity was found to be very high within the marine muds of Unit 1 (Fig. 5). This evidence does contradict other species assemblage and isotopic studies from Svalbard, which suggest a phase of cooling by 8 cal. ka BP that intensified at 4 cal. ka BP [28, 29, 51, 58, 59]. However, increased inflow of Atlantic water
between 7.6 and 6 cal. ka BP was found in the northern Barents Sea [60]. The widely observed increase in *E. clavatum* associated with polar water [28, 59] is also delayed in the Storfjorden Trough, occurring at about 5-6 cal. ka BP [14], and thus Rasmussen et al. [59] have acknowledged regional differences. Studies of terrestrial glacier advances and lacustrine sediments also favour a scenario in which cooling pulses occurred between ~4.6-3 cal. ka BP [61, 62]. A possible explanation could be that Forlandsundet is very open to Atlantic water, and that the geostrophic control exerted on fjord-shelf exchange [63, 64] may be less significant for this strait than adjacent fjords.

### Conclusions

The geomorphological and marine sedimentological data presented in this paper shows evidence of a fully glaciated inter-ice stream margin during the LGM. Whilst previous studies have concluded that an ice-free enclave would have been highly unlikely due to the dynamics and extent of the SBSIS [6], this investigation confirms these assumptions and reveals complex glaciological and oceanographic dynamics since at least the LGM.

- We interpret subglacial sediments suggesting presence of grounded glacial ice at 15 cal. ka BP from the marine record in Forlandsundet.
- We infer from the geomorphology of Forlandsundet that the ice flow was topographically controlled only during deglaciation. Cold-based glacier ice likely prevented the formation of E-W trending lineations during maximum extent of the SBSIS and preserved the pre-LGM raised beaches on Prins Karls Forland.
- Glacier retreat was stepwise during the Bølling–Allerød interstadial and Younger Dryas, with possible stillstands and minor readvances before inflow of warm Atlantic water led to the rapid decay of glacier ice in the early Holocene.
- Large parts of the early to mid-Holocene sediment record were removed, hinting at the complexity of environmental conditions, with slope instabilities or bottom current erosion as the most likely cause.
- Late Holocene cooling is evident in the faunal assemblage, as well as the geomorphological assemblages pointing at growth of several outlet glaciers during the Little Ice Age. The later onset of Holocene cooling is explained by the hydrography of Forlandsundet, open to the inflow of Atlantic water.

### Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.
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Fig. 2: (a) Zoomed view of Dahlbrebukta with multibeam bathymetry, aerial orthophotos [65] as well as a 5m terrestrial digital elevation model [66] and (b) close-up aerial imagery from the Dahlbreen glacier foreland showing remnant CSR.
Fig. 3: Hill-shade images of bedform features and bathymetric profiles: (a) and (b) lineations overprinted by transverse ridges, (c) elongate streamlined features tapering off to the east, (d) large ridge segment in east of Eidembreen’s glacier margin, (d) subparallel lineations in the seabed, (f) steep longitudinal ridges running approximately north to south.

Fig. 4: Composite log of sediment core HH13-03-GC with (A) lithological properties including radiocarbon dates and facies codes (Fm – massive fines, Fl – laminated Fines, Dmm – matrix-supported massive Diamicton, Dm – matrix-supported diamicton, (d) evidence of dropstones) and (B) magnetic susceptibility, (C) shear strength (D) bulk density and (E) grain size in percentage volume for the <1mm fraction and (F) percentage weight for grains >1 mm.

Fig. 5: Stratigraphic diagram of the benthic foraminifera assemblage, with relative concentration (%) and flux of benthic foraminifera (tests cm⁻² ka⁻¹) plotted against depth bsf (cm) in C2 [61], with a Bacon R age-depth model on the right to correlate core depth with age [36]. The dotted line at 230 cm bsf indicates the subsample barren of foraminifera and solid horizontal lines indicate unit boundaries.

Fig. 6: Conceptual model for ice flow and deglaciation of Forlandsundet: (a) showing tributary ice flow during deglaciation following the LGM, (b) a still-stand at or readvance to the grounding zone wedge during the Older Dryas, (c) ice in a Younger Dryas retreat position, and (d) modern glacier extent. This reconstruction was created using DTMs available online from the Norwegian Polar Institute [66].

Table 1: ¹⁴C dates, sample material and calibrated calendar ages for sediment core HH13-04-GC

<table>
<thead>
<tr>
<th>Core depth</th>
<th>Sample ID</th>
<th>Material</th>
<th>¹⁴C Age BP (BP)</th>
<th>Cal. yr BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 cm</td>
<td>UBA-31507</td>
<td>mixed benthic foraminifera</td>
<td>6,546 ± 35</td>
<td>6,939</td>
</tr>
<tr>
<td>150 cm</td>
<td>UBA-31508</td>
<td>N. labradorica</td>
<td>10,729 ± 45</td>
<td>12,043</td>
</tr>
<tr>
<td>270 cm</td>
<td>UBA-31509</td>
<td>benthic foraminifera and ostracod shells</td>
<td>12,629 ± 62</td>
<td>14,151</td>
</tr>
</tbody>
</table>