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Evidence for an extensive ice shelf in northern Baffin Bay during the Last Glacial Maximum

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Abstract

The glaciological significance of ice shelves is relatively well established for the stability of modern ice sheets of Antarctica. Past ice shelves of the Arctic, however, are poorly documented while their role for the stability of former ice sheets remains mostly unknown. Here we present swath bathymetry data and seismostratigraphic profiles that reveal a large moraine system extending along the continental slope off Baffin Island, demonstrating that a 500-m thick ice shelf covered northern Baffin Bay during the last glacial episode. We suggest that this ice shelf had a profound impact on the stability of a series of major ice streams that drained the interior of the Laurentide, Innuitian and Greenland ice sheets. Climate warming and global sea-level rise in the early stage of deglaciation possibly contributed to a large-scale break-up of the ice shelf, which led to the destabilisation and reorganisation of tributary ice streams from these three ice sheets.

Introduction

Ice shelves are critical components of marine-terminating ice sheets due to their buttressing effect that controls mass balance by stabilizing the ice margins facing the ocean[1-7]. Retreat and break-up of ice shelves in Antarctica[2,3,6,8-11] occur today at a time of important climate warming and may lead to a drawdown of the West Antarctic Ice Sheet, resulting in a rapid transfer of ice to the ocean and thereby contributing to global sea-level rise[1,2,11,12]. Identifying former ice shelves and reconstructing their evolution through time –particularly for past ice sheets of the Northern Hemisphere where they remain poorly documented[3,12,13]– will provide an essential analogue for understanding the stability of modern ice sheets and their interplay with climate and global sea-level change.

Baffin Bay forms a 450 km-wide and 2000 m-deep embayment between the Canadian Arctic Archipelago and Greenland (Fig. 1). At the Last Glacial Maximum (LGM; locally ~25-16 ka BP), Baffin Bay was located at the confluence of three ice sheets –the Laurentide (LIS), Innuitian (IIS) and Greenland (GrIS) ice sheets[14-17]– forming a continuous belt of ice streams draining the interior of Northern North America and Greenland and extending at or near the continental shelf break in many sectors[18-26]. However, the extension of these ice sheets beyond their grounding zones to form floating ice shelves remains elusive. The scenario of ice shelves in the northern Hemisphere have been hypothesized repeatedly since it was first introduced by Mercer[27] as a comparison between the Arctic Ocean and West Antarctica. Hughes et al.[28] later expanded the idea to include floating ice shelves in Baffin Bay and eastern North America. The scenario of an ice shelf extending in Baffin Bay from a southern source of ice grounded in Davis Strait and associated with the Hudson Strait Ice Stream was speculated by Hulbe[29] as a starting point to explain the mechanisms behind Heinrich events. Although Hulbe et al.[30] modified their original stance to instead support fringing ice shelves along the coasts of Eastern Canada, the idea of an extensive ice shelf sealing Baffin Bay from the Labrador Sea was adopted in the following decades[31,32] although still debated as a trigger mechanism for Heinrich events[33]. However, this scenario was recently refuted by Jennings et al.[34] who argued that such an ice shelf would have impeded Labrador Sea water advection, a key component for biological productivity observed at the LGM in cores off western Greenland. They suggested instead that the GrIS margin was protected by either a belt of fringing ice shelves and/or perennial sea-ice –a scenario in line with Hulbe et al.[30]– that prevented deposition of ice-rafted debris (IRD) and enabled marine advection and food supply during the LGM. Alternatively, a scenario of an ice shelf from a northern source of ice grounded in northern Baffin Bay has been so far unaddressed, in a context where the marine-terminating Lancaster Sound and Smith Sound ice streams captured several major tributaries from the LIS, IIS and GrIS[17,21], creating ideal conditions for the formation of an ice shelf that potentially controlled the stability of other ice streams outflowing from the eastern Canadian Arctic Archipelago and western Greenland[17,24,25].

Solving the ice shelf issue in Baffin Bay is therefore necessary for evaluating the effects of buttressing on ice flow, ice streams stability and ice sheet mass balance changes during a key stage of deglaciation of the Arctic and a period of major meltwater flow into the ocean. Here we present geophysical (swath bathymetry, acoustic profiles) datasets and a compilation of previously published sediment core data collected on the outer sector of the cross-shelf trough off Clyde Inlet (Baffin Island) and its adjacent continental slope of western Baffin Bay that together demonstrate the existence of an ice shelf in northern Baffin Bay –the Northern Baffin Bay Ice Shelf (NBBIS)– during the last glacial episode (Fig. 1). This geomorphological evidence and the re-interpretation of sediment cores allow defining the extent of the LIS on the continental shelf at the LGM and examining the potential impact of an ice shelf collapse on the evolution of ice streams of the three marine-terminating ice sheets in Baffin Bay.

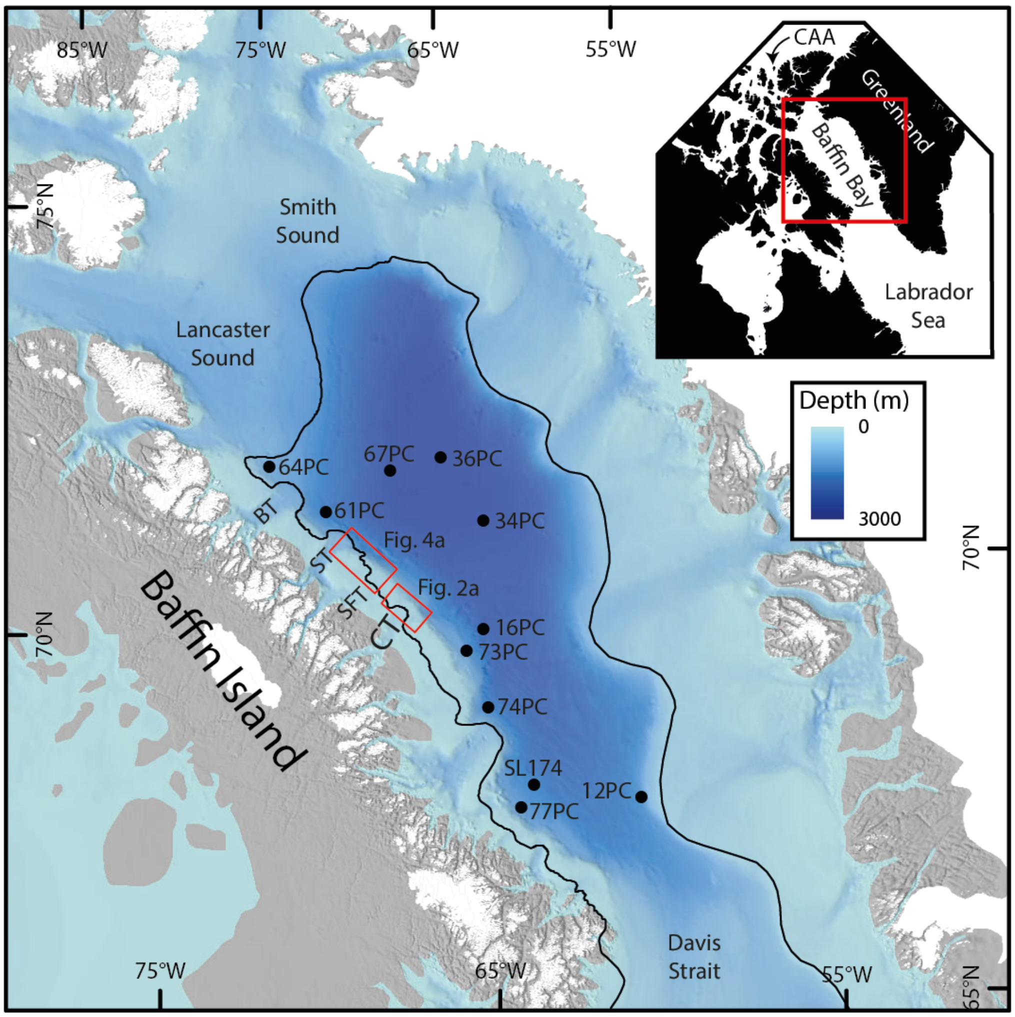

Fig. 1: Location map of the investigated area. Location of Clyde Trough (CT), sediment cores and maximum extent of grounded ice on western Baffin Bay (thick line), compiled and modified from previous works[21,25,26] and this paper. BT: Buchan Trough; ST: Scott Trough; SFT: Sam Ford Trough. Red rectangles represent study areas shown in greater details in Figs 2 and 5. (Inset) Location of Baffin Bay north of the Labrador Sea and between Greenland (GR) and the Canadian Arctic Archipelago (CAA).

Results and discussion

The geomorphological signature of the NBBIS

Three ridges running in parallel to the continental slope off Clyde Trough between 300 and 420 meters below sea-level (mbsl) are observed on the swath bathymetry imagery (Fig. 2a-b). These ridges are independent from grounding zone wedges (GZWs) constructed by outlet glaciers and ice streams emanating from Baffin Island. The central ridge is the largest; it is 30 m high, ~300-m wide and extends almost continuously for >30 km along the slope off Clyde Trough (Fig. 2a and 3). It has an asymmetric profile showing a gentler ocean-facing slope and is observed at progressively decreasing depths from north (330 mbsl) to south (300 mbsl). Although it appears to be streamlined along the continental slope, one of the segments of the central ridge (Fig. 2b and 2c) shows evidence of sediment accretion by ice push in a NW-SE direction (i.e., towards Baffin Island). Additionally, two 5-10 m-high subdued ridges occur on both sides of the main ridge at 420 and 310 mbsl, extending for <5 km in front of Clyde Trough and showing geomorphic similarities to the neighbouring central ridge (Fig. 2b). Similar ridges are also observed at 350 mbsl off Sam Ford Trough and 410 mbsl south of Scott Trough, 40 and 100 km northwest of Clyde Trough, respectively (Fig. 4). These ridges probably correspond to the central ridge observed on the upper continental slope off Clyde Trough as they are also ~30 m high with a gentler ocean-facing slope.

We rule out the possibility of these landforms being terminal moraines of the LIS on the upper continental slope as its geometry does not appear to be influence by the location of cross-shelf troughs. If they indeed originated from flowing ice across the Baffin Island continental shelf, one would expect some bulge in front of the trough. Instead, we observe a curvature in the orientation of these ridges into Clyde Trough (Fig. 2a). These ridges are therefore interpreted as lateral moraines of the NBBIS on the basis of (a) their geomorphology similar to previously reported ice-shelf moraines in the Canadian Arctic Archipelago[35-40], and (b) their location, depth and orientation along the continental slope off Baffin Island. The progressively decreasing depths of these ice shelf lateral moraines comply with a paleoglaciological reconstruction including a seaward thinning of the ice shelf. The smaller subdued ridges could represent different phases and/or thickness changes of the NBBIS during the LGM, although their relatively subdued appearance could also suggest formation during prior glaciations (i.e., MIS-6).

In outer Clyde Trough (Fig. 2a and 3), the absence of gullies on the trough-mouth fan and of streamlined glacial bedforms at the continental shelf edge suggest that the Clyde Ice Stream (CIS) did not reach the continental shelf break at the LGM –in contrast with other ice streams on northeastern Baffin Island[25]– and was probably not connected to the NBBIS. This disconnection between the CIS and the NBBIS in outer Clyde Trough is supported by the presence of two GZWs located ~10 km landward from the continental shelf edge and ~15 km west of the slope ridge system (Fig. 5), leaving an open area between the CIS margin in the outer trough and the grounded NBBIS on the slope.

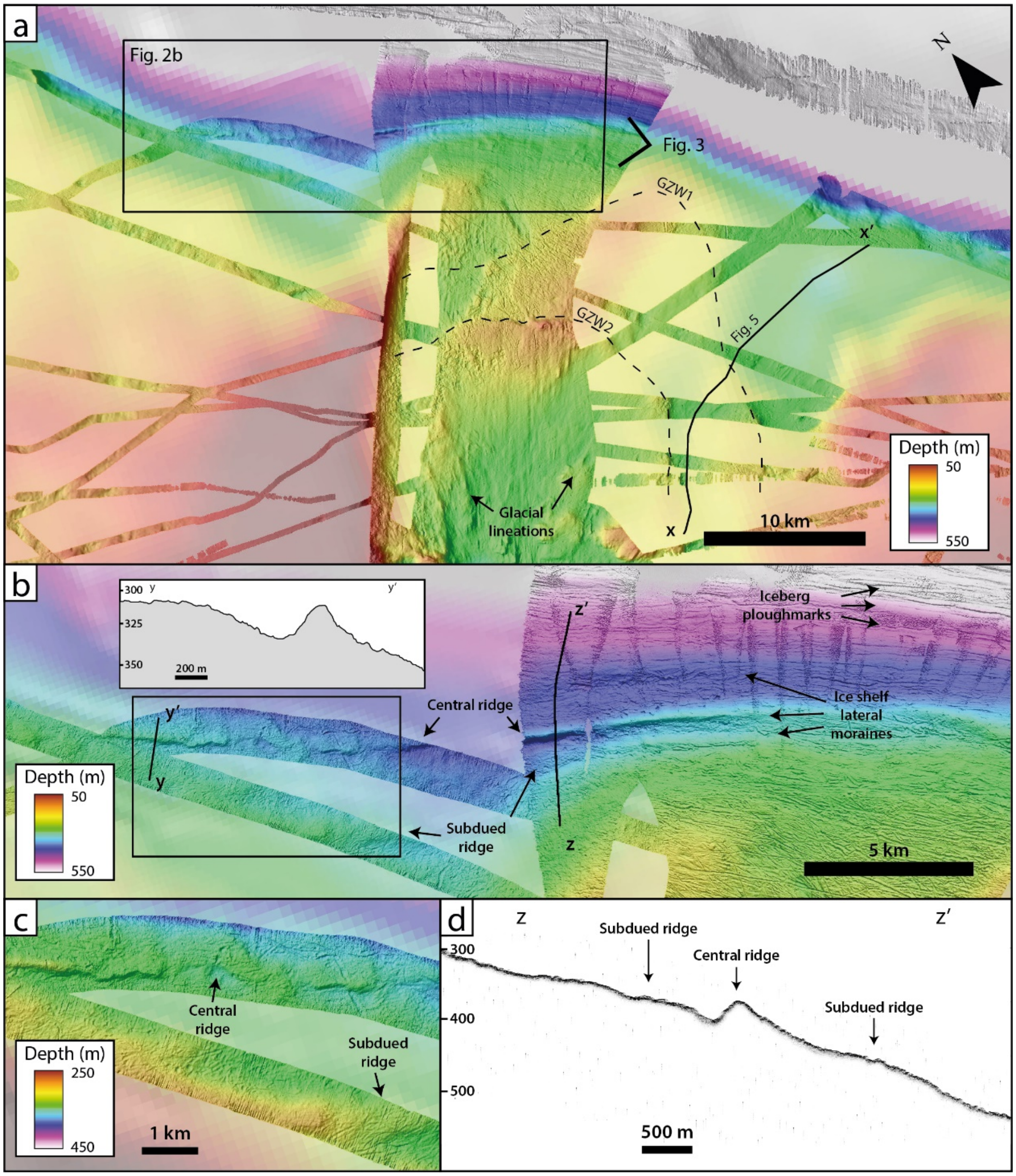

Fig. 2: Geophysical data along the Baffin Shelf margin off Clyde Trough. (a) Bathymetry of the outer Clyde Trough and adjacent upper continental slope. Dashed lines represent GZW1 and GZW2 positions. (b) Bathymetry along the continental slope of off Clyde Inlet showing the ice shelf lateral moraines and the deep iceberg ploughmarks. (Inset in b) Bathymetric profile across the ice shelf lateral moraine. (c) Zoom on the central ridge of the ice shelf lateral moraine. (d) Parasound profile across the ice shelf lateral moraine.

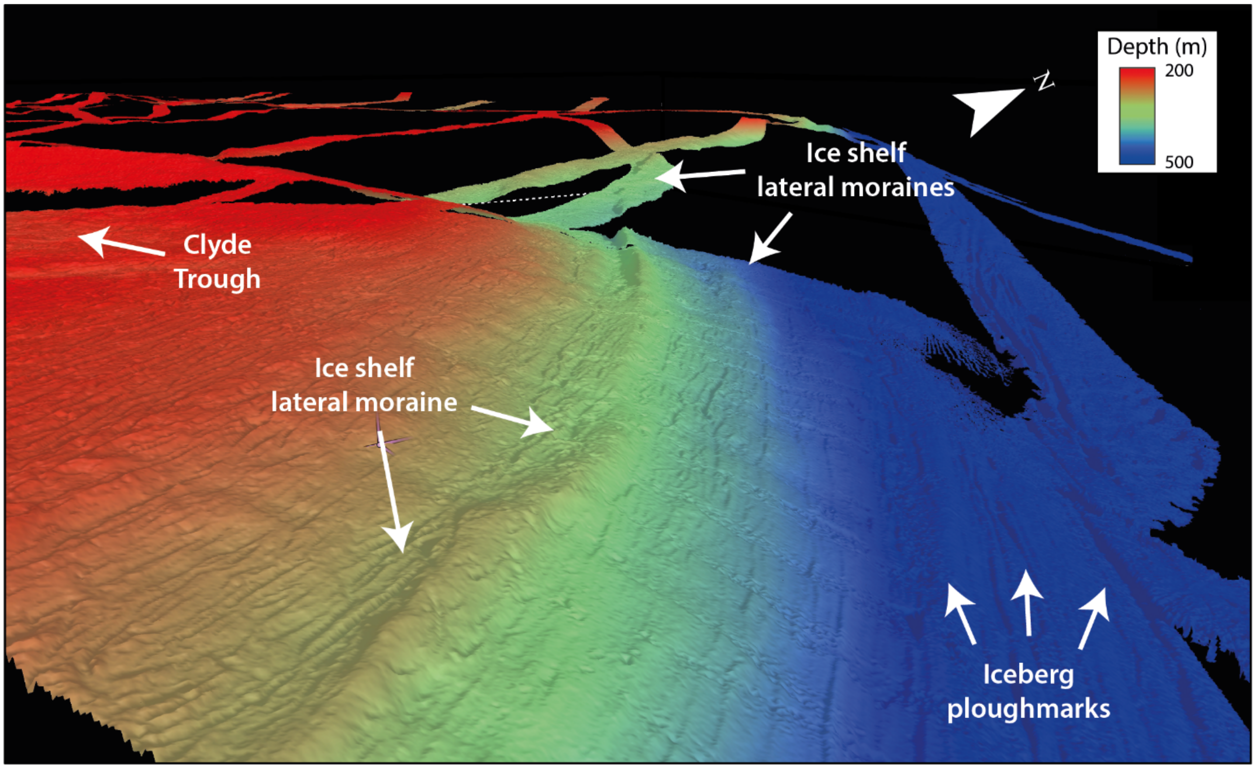

Fig. 3: The ice shelf lateral moraines on the continental slope off Clyde Trough. 3D imagery generated using the QPS Fledermaus software showing the ice shelf lateral moraines and iceberg ploughmarks.

More to the north, a GZW located ~20 km off Scott Trough at ~450 mbsl and associated with streamlined bedforms oriented parallel to the continental slope indicate grounded ice flowing southeastward along the shelf (Fig. 4a and 4b). The streamlined bedforms are similar to mega-scale glacial lineations[41-43] or sub-ice shelf keel scours[6,44] and were recognized to be the product of ploughing across the seafloor by an ice shelf. This system therefore suggests that ice flowing out of the Scott Trough was either 1) deflected from its along-trough original flow by an obstacle (i.e., a floating ice shelf in Baffin Bay); or 2) a large independent ice body expanding all the way up to Clyde Trough (i.e., a fringing ice shelf). The first hypothesis is more probable as there is no explanation for the divergence of the Scott Ice Stream from an along-trough to along-slope orientation without a buttressing mechanism. These landforms, together with the ice shelf lateral moraines observed at shallower depths than the bottom of Scott Trough (>600 mbsl; Supplementary Fig. 1), suggest that, in contrast to Clyde Trough, the Scott Ice Stream –and probably other systems of northeastern Baffin Island– merged with the NBBIS. Mega-scale glacial lineations, ice stream lateral moraine and 'lift-off' moraines identified by Brouard and Lajeunesse[25] on the Scott trough-mouth fan in turn indicate an ice streaming phase extending to the shelf edge (Fig. 4a). Initially interpreted as features of LGM ages[25], they could instead correspond to a local subsequent readvance prior to 14.2 kyr BP[45].

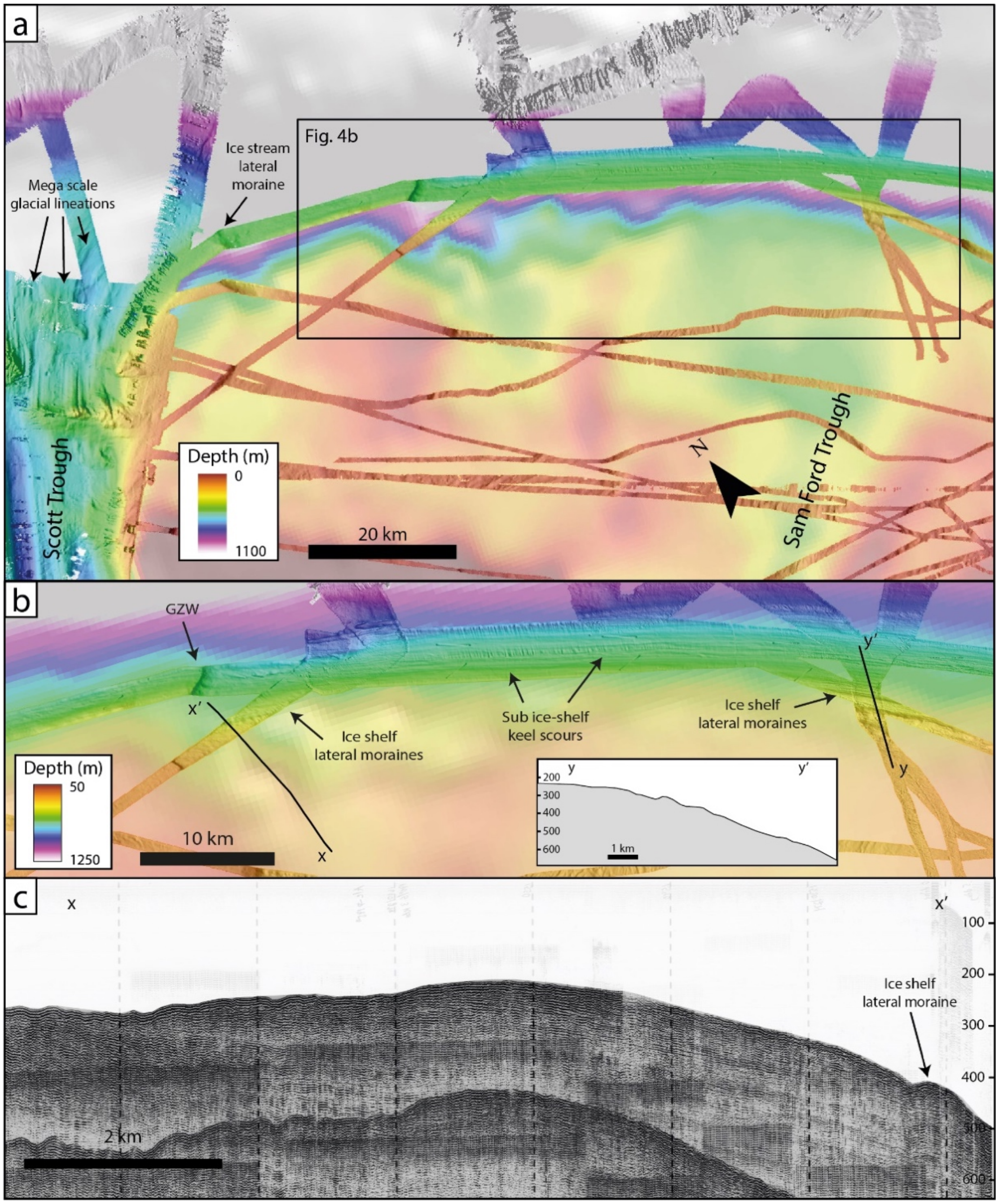

Fig. 4: Geophysical data along the northwestern Baffin Shelf margin. (a) Bathymetry of the upper continental slope between Scott Trough and Clyde Trough (see Fig. 1). (b) Bathymetry along the continental slope of Baffin Island showing a GZW south of Scott Trough aligned with the ice shelf lateral moraine and sub-ice shelf keel scours. (Inset in b) bathymetric profile of the ice shelf lateral moraine near Sam Ford Trough. (c) Airgun profile 78029_AG_274_1516 showing the ice shelf lateral moraine near Scott Trough.

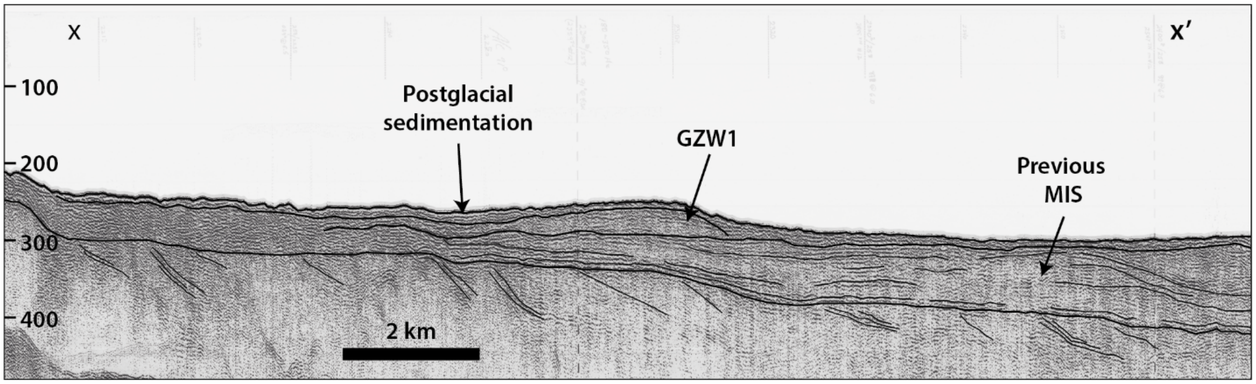

Fig. 5: Seismic evidence of ice extent in Clyde Trough. Airgun profile 80028_AG_RAYT_257_0200 showing GZW1 and deeply buried glacigenic debris-flows in outer Clyde Trough (location in Fig. 2a).

In addition, the continental slope along Baffin Island is heavily affected by curvilinear scours between 5-10 m deep and down to >750 mbsl (Figs. 2a, 3 and 4a). These scours, interpreted as iceberg ploughmarks, indicate extensive calving from a thicker body of ice in northern Baffin Bay probably after the LGM[15].

The available swath bathymetry and seismostratigraphic data do not allow identifying ice shelf lateral moraines south of Clyde Trough with confidence and, therefore, precisely addressing the NBBIS extent toward southern Baffin Bay. Faint bedforms similar to those presented above are observed on the bathymetry some 120 km to the south, but their association with those off Clyde Trough is ambiguous as they are located at greater depths (400 mbsl; Supplementary Fig. 2). The timing of formation of this lateral ice-shelf moraine is also unknown as no sediment core, thus no direct dating, were retrieved on this bedform. In this context, the presence of an extensive ice shelf on the Arctic ocean during MIS-6[42,46] could suggest contemporaneity on Baffin Bay. Such an ice shelf is supported by a raised marine sediment sequence identified on Eastern Baffin Island[47,48] that was dated at this period[49], suggesting a more extensive ice cover during the penultimate glaciation. Additionally, several studies provided evidence for the presence of the LIS along the eastern margin of Baffin Island throughout MIS-4 to MIS-2[50-55]. However, sediment records in Baffin Bay and along the Baffin Island continental shelf allow discussing the potential timing and extent of the NBBIS.

The sedimentary signature of the NBBIS

The previously published sediment records from Baffin Bay (Fig. 6)[14,21,45,56-60] are compatible with the presence of an ice shelf during the LGM. The buildup of ice sheet in northern Baffin Bay prior to the LGM is marked by a layer of IRD and carbonate-rich sediments originated from northern Baffin Bay termed Baffin Bay Detrital Carbonate (BBDC) layer, which is identified basin-wide and dated between 26-24.7 kyr BP (BBDC-2[45,56,57,60]). The quasi-absence of IRD throughout the LGM (~24.7-~16.5 kyr BP) in most cores of Baffin Bay suggests an extensive ice cover, either as perennial sea ice[61] or an ice shelf[6,34]. The occasional clasts observed in some cores of northern

Baffin Bay could be explained by their relatively short distance from the ice grounding line as it is affected by mass flows and the rain out of ice shelf basal debris[6,33,62,63,64]. Provenance study on core 16PC, located 100 km east of Clyde Trough in central Baffin Bay (Fig. 1), shows uniform mineralogic composition dominated by a Greenland-sourced sediment assemblage and a restricted Baffin Island-sourced input during the LGM interval[57]. Localized and uniform mineralogic assemblages are typical of sub-ice shelf setting reflecting uniform conditions in which transport is dominated by meltwater plumes[6,65]. A coarsening-upward trend with frequent IRD in cores of Baffin Bay starts at ~16.5 kyr BP[57,58,60] and is followed by the deposition of carbonate-rich BBDC-1 between ~14.5 and ~13.7 kyr BP[57,60]. Such a coarsening-upward sequence typifies the progressively more open water conditions that usually follow ice shelf collapse events[6,64]. This sedimentary record is therefore in support to the hypothesis of an ice shelf in Baffin Bay during the LGM. In addition, it provides a time framework suggesting that break-up started at ~16.5 kyr BP and ended with the onset of BBDC-1 at ~14.5 kyr BP[15,57,60].

Sediment cores collected on the Baffin Island continental slope (Fig. 6) allow defining the position of the LIS margin on the continental shelf off Baffin Island during the LGM and early deglaciation. The base of most cores is marked by ice-proximal dark grey-brown diamicton interpreted as glacigenic debris-flows deposits and correlated to an ice advance at ~25 kyr BP[45]. In 77PC, a gold brown mud layer located halfway along the core was correlated to BBDC-2[26,45] and therefore correspond to the ice advance observed in the other cores along the continental slope. Provenance study on this core indicates that a localized source of carbonate sediments, originating from a Paleozoic outcrop east of the Home Bay[66,67], area also contributed to the composition of the gold brown mud layer[68]. Cores from the continental slope offshore Baffin Island (Fig. 1) typically consist of laminated red brown mud with rare or absent IRD during the LGM interval. Jenner et al.[45] noted, however, that coarse IRD-rich beds from the basal diamicton gradually decrease in abundance upwards into laminated red brown mud and very fine sand with IRD in cores 61PC off Scott Trough. These laminated red brown muds are interpreted as lateral sediment supply from NE Baffin Island, as they thin in deeper water off the trough mouth fans[14,45], an interpretation corroborated by their mineral composition[60]. They are, however, absent in core 73PC (Fig. 1), suggesting the absence of grounded ice at the shelf break in Clyde Trough during the LGM, in line with the receded position of GZWs and the presence of predominantly Greenland-sourced sediments in core 16PC[58]. Except for 77PC, located off Home Bay in southern Baffin Bay, the laminated red brown muds are characterized by an absence of bioturbation and microfossils[45]. According to the ice-shelf sedimentary model of Smith et al.[6], this sequence might represent an ice advance to the continental shelf edge at the LGM (stratified diamicton), followed by ice shelf buildup with frequent iceberg calving (turbidites interbedded with IRD layers) and, ultimately, a full ice shelf cover (laminated red brown mud). A second diamicton overlying the red brown laminated muds is observed immediately below BBDC-1 in cores north of Clyde Trough[45,69], representing glacigenic debris-flows deposits correlated to a smaller localized advance from northeastern Baffin Island ice streams to the shelf break prior to 14.2 kyr BP[45].

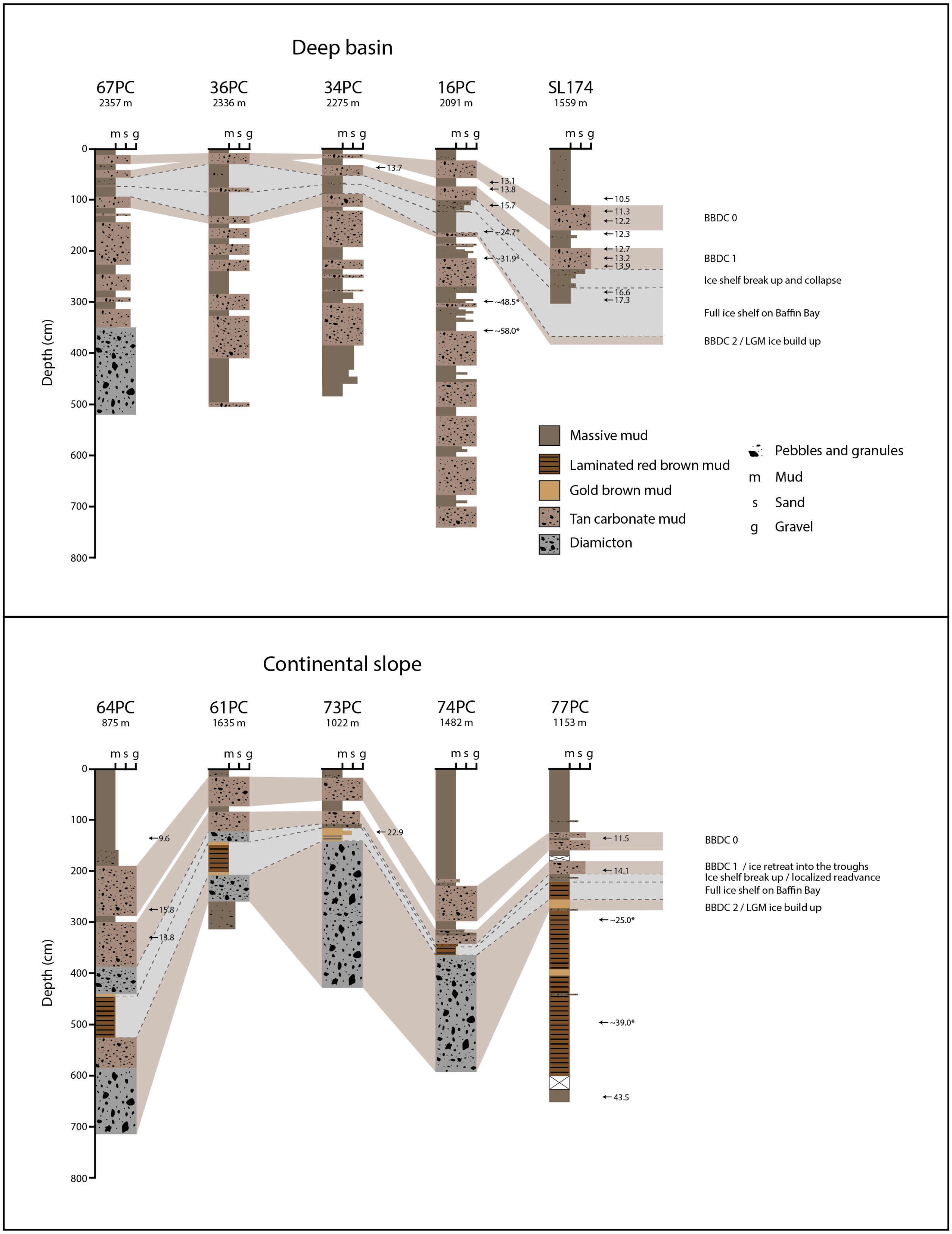
Deep basin
67PC
2357 m
36PC
2336 m
34PC
2275 m
16PC
2091 m
SL174
1559 m
m s g
Depth (cm)
0
100
200
300
400
500
600
700
800
13.7
13.1
13.8
15.7
~24.7*
~31.9*
~48.5*
~58.0*
10.5
11.3
12.2
12.3
12.7
13.2
13.9
16.6
17.3
BBDC 0
BBDC 1
Ice shelf break up and collapse
Full ice shelf on Baffin Bay
BBDC 2 / LGM ice build up
Massive mud
Laminated red brown mud
Gold brown mud
Tan carbonate mud
Diamicton
Pebbles and granules
m Mud
s Sand
g Gravel
Continental slope
64PC
875 m
61PC
1635 m
73PC
1022 m
74PC
1482 m
77PC
1153 m
9.6
15.8
13.8
22.9
11.5
14.1
~25.0*
~39.0*
43.5
BBDC 0
BBDC 1 / ice retreat into the troughs
Ice shelf break up / localized readvance
Full ice shelf on Baffin Bay
BBDC 2 / LGM ice build up

Fig. 6: Sediment assemblages in Baffin Bay and along the Baffin Shelf. Lithology of piston cores from Baffin Bay modified from various published datasets (see methods). Radiocarbon ages are reinterpreted in calendar years using the online software Calib 8.2 with the Marine20 radiocarbon age calibration curve[87] and a local reservoir correction (ΔR) of 87±20[88]. Additionally, relative paleointensity (*) chronology is also presented for core 16PC[59] and 77PC[26]. Correlations are based on Baffin Bay detrital carbonate (BBDC) beds and are compiled from original publications. BBDC events are represented by the brown shaded areas – ages are from Simon et al.[57] and Jackson et al.[60]: BBDC-2: ~25-24.7 kyr BP; BBDC-1: ~14.2-13.7 kyr BP; BBDC-0: ~12.7-11 kyr BP. The grey shaded horizon represents ice shelf setting on Baffin Bay; note the quasi-absence of IRD during that interval.

To our knowledge, no sediment core has been collected or published from the Greenland side of northern Baffin Bay to allow direct comparison with Baffin Island continental slope assemblages. In southern Baffin Bay, sediment core data show similar sequence as those from the Baffin Island continental slope[34,70,71]. However, widespread foraminifera assemblages and bioturbation during the LGM interval suggest the presence of perennial sea-ice[61] and/or a nearby ice shelf margin[62,72,73]. A thorough discussion on sediment assemblages and their relation to ice shelf and/or perennial sea-ice on the continental slope of western Greenland was provided by Jennings et al.[34].

Evidence of ice shelf inception in northern Baffin Bay

The presence of an ice shelf in northern Baffin Bay at the LGM and during the early stage of deglaciation is supported by invoking the Marine Ice Cliff Instability (MICI) theory, which stipulates that fracturing due to longitudinal stresses exceeding the yield strength initiate ice cliff failures when a marine-based ice-margin reaches ~1 km in thickness[74-76]. Till wedges, GZWs and mega-scale glacial lineations identified on the upper continental slope off Lancaster Sound[21,25] and Smith Sound (Supplementary Fig. 2) indicate grounded ice as deep as 1350 mbsl. Accounting for a coeval higher relative sea-level (RSL) of ~75 m based on the modeled RSL values from a nearby Baffin Island site[77], ice thickness can be estimated using:

$$H_{LGM} = (\rho_w/\rho_i) \cdot (D+\Delta D_{LGM}) \qquad (1)$$

where H_{LGM} is the minimum ice thickness during the LGM, $\rho_w = 1028$ kg m^{-3} and $\rho_i = 910$ kg m^{-3} are the mean densities of sea water and ice, respectively, D is the water depth and ΔD_{LGM} is the correction for water depth at the LGM[74]. In the case of the Lancaster Sound and Smith Sound trough-mouth fans, grounded ice had to be >1550 m-thick. The Lancaster Sound till wedges and the Smith Sound GZW could not have been deposited without an ice shelf buttressing –and temporarily stabilising– the front of these ice streams[4,76,78]. In order to maintain a stable position without an ice shelf in northern Baffin Bay, the ice margin would have needed to retreat until it reached the theoretical depth of ~800 m, hence continually calving icebergs throughout the LGM[76]. Such a constant calving in northern Baffin Bay is, however, not compatible with the sedimentary record from the slope and deep basin off Baffin Island (Fig. 6) where a quasi-absence of IRD was observed during this interval. Moreover, numerical models indicate that ice grounded at 1500 mbsl is expected to form a ~500 m-thick ice shelf[79]; a thickness consistent with observations off Clyde Trough where ice shelf lateral moraines are observed at ~400 mbsl (i.e., ~475 m at the LGM).

Implications of a NBBIS

Glacial landforms and deposits off Baffin Island continental shelf combined with the Baffin Bay sedimentary record provide definitive evidence for the presence of a 500 m-thick ice shelf in northern Baffin Bay at and shortly after the LGM. The scenario of an ice shelf fed by ice streams located in northern Baffin Bay does not require grounded ice in Davis Strait sealing inflow of food supply from Labrador Sea waters, therefore reconciling with biological productivity observations on the continental slopes of southern Baffin Bay during the LGM[34,45]. This scenario provides a framework for revising the glaciation development around Baffin Bay and reassessing the potential impacts of the ice shelf collapse on the reorganisation of major ice streams draining the LIS, IIS and GrIS during the last glacial cycle (Fig. 7).

Ice shelf inception at the LGM: Based on the presence of BBDC-2 and diamicton along the margin of eastern Baffin Island, the NBBIS probably started building up with an advancing ice shelf margin across Baffin Bay between ~26 and ~24.7 kyr BP. The presence of the short-lived BBDC-3 event[44] suggests an earlier buildup with frequent break-up of the NBBIS margin. This earlier buildup would be in line with the presence of the LIS on the Baffin Island continental shelf –and possibly Lancaster Sound– during MIS-3[50-55]. An extensive LIS during MIS-3 would likely have facilitated an earlier advance of the ice margin across the other shelves surrounding Baffin Bay. Regardless of the exact timing of ice shelf inception in northern Baffin Bay, grounded ice flowing from Lancaster Sound and Smith Sound fed the NBBIS between at least ~24.7 and ~16.5 kyr BP, which in turn buttressed peripheral glaciers and ice streams of the eastern Canadian Arctic Archipelago and possibly Western Greenland. The available geological record allows identifying the southward extent of the NBBIS at least down to the latitudes of Clyde Trough. The relatively shallow depths of the ice shelf lateral moraine in front of Clyde Inlet (<350m) suggests that the ice shelf was thinning and its margin was possibly located nearby, therefore making it difficult to extend farther south to Home Bay and preserve a constant thickness of ~500m for >100km. Although geophysical data from the Greenland continental shelf do not allow confirmation, it is probable that the ice shelf had a similar extent across the entire Baffin Bay. The relatively deep troughs (<500 mbsl) on the Greenland side of northern Baffin Bay possibly prevented the formation of ice shelf lateral moraines. Similarly to northeastern Baffin Island, ice streams located off the GrIS may have merged with the NBBIS. The exact extent of the NBBIS in southern Baffin Bay remains unknown; sediment assemblages[45,60] show similarities to those of northern Baffin Bay, while the record of marine productivity during the LGM suggests openings in sea-ice as polynias and/or advection under a proximal ice-shelf margin[34]. It is therefore possible that, while northern Baffin Bay was covered by a basin-wide ice shelf system, southern Baffin Bay was characterized by fringing ice shelf and/or perennial sea-ice along both continental shelves, which could explain the presence of ice shelf lateral moraines off Home Bay.

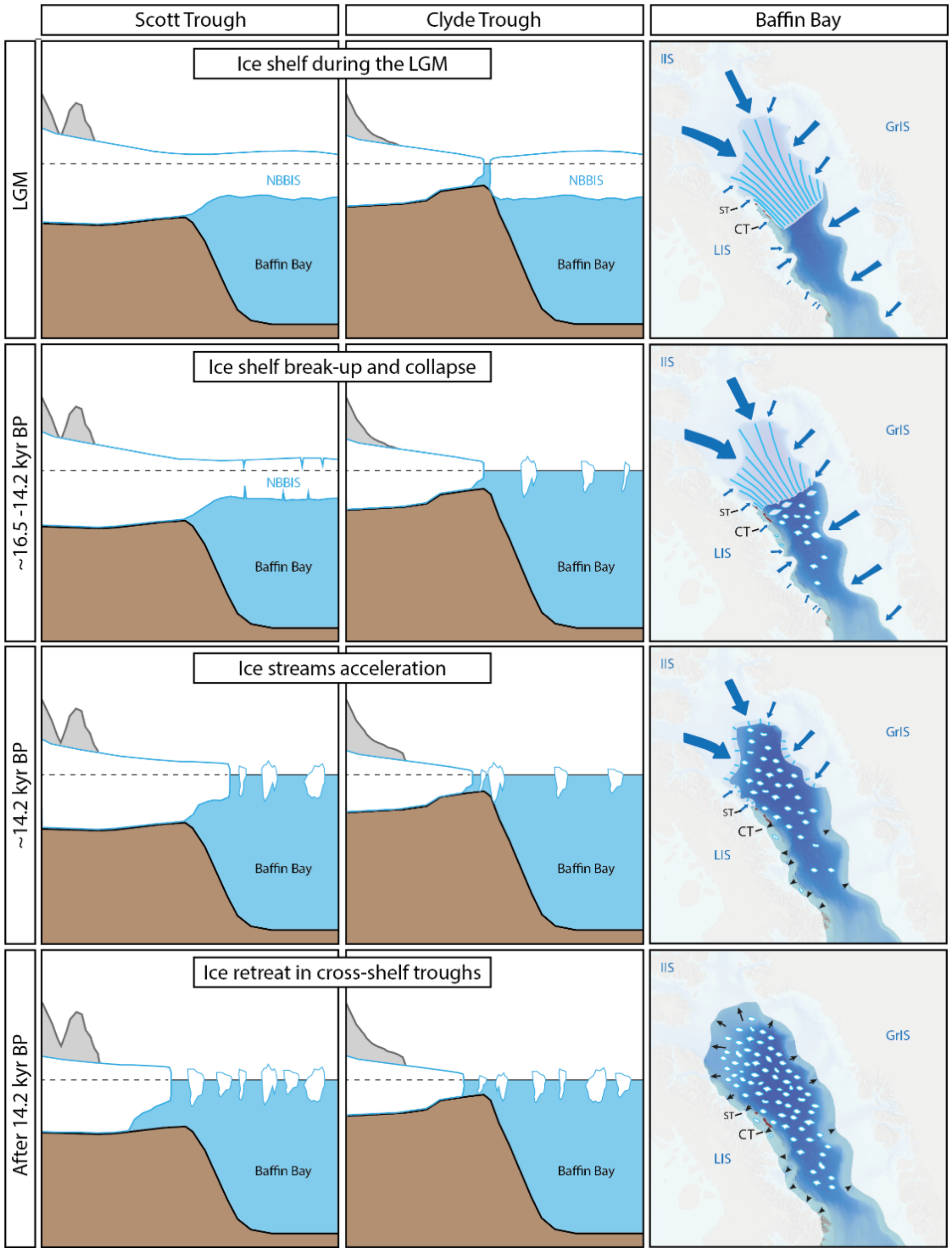

Fig. 7: Conceptual model for early deglaciation including the NBBIS and the LIS outlets in Baffin Bay. Reconstruction of ice sheets in Baffin Bay during the LGM and subsequent deglaciation. LIS: Laurentide Ice Sheet; IIS: Innuitian Ice Sheet; and GrIS: Greenland Ice Sheet. CT: Clyde Trough; ST: Scott Trough. Blue arrows indicate an advancing or stable ice margin and black triangles indicate a retreating ice margin. Brown lines represent ice shelf lateral moraines along Baffin Island continental shelf.

Ice shelf break-up and collapse: Rising sea level and/or enhanced incursion of relatively warm Atlantic waters via the Western Greenland Current[34,80] may have provoked a destabilization and collapse of the NBBIS front between ~16.5 and ~14.2 kyr BP (Supplementary Fig. 3). The initiation of this break-up is recorded by an increase in IRD and coarse-grained sediments in cores from Baffin Bay[57,60]. Such a break-up would have been accelerated by warming summer temperatures[81] providing the necessary heat to produce sufficient meltwater to fill crevasses and induce hydrofracturing [10,11], in turn favouring the production of small icebergs rather than large tabular icebergs [1,4,30]. The final collapse of the NBBIS corresponds to the onset of widespread delivery of northern Baffin Bay-sourced detrital carbonates in Baffin Bay – BBDC-1[15,58,60].

Ice streams acceleration: As the NBBIS rapidly collapsed by ~14.2 kyr BP, ice streams of northeastern Baffin Island became unbuttressed, thereby thinning due to their acceleration, similarly to observations made on present-day ice shelves in Antarctica[1,5,7,8]. The accelerated discharge from northeastern Baffin Island ice streams probably led to the deposition of the younger diamicton identified on the continental slope north of Clyde Trough[45]. The MSGLs and ice stream lateral moraine at the shelf edge in Buchan and Scott troughs[25] further supports this acceleration of ice streams. The presence of 'lift-off' moraines at the shelf break[25] suggests tidally related buoyancy at the grounded ice sheet margin[82], which could potentially be a sign of ice stream thinning. The absence of the second diamicton south of Clyde Trough suggests that no readvance nor glacier acceleration occured in Clyde Trough, probably because the CIS was not initially buttressed by the NBBIS. The occurence of ridges similar to 'lift-off' moraines on Melville Bay trough-mouth fans[24] could hint to a similar history as northeastern Baffin Island ice streams. Ice streams acceleration around northern Baffin Bay are coeval to a period marked by exceptionally high rates of global sea-level rise (Meltwater Pulse 1A[12,83,84]) suggesting contribution of the North America high-arctic ice sheets to this event.

Ice retreat in cross-shelf troughs: Ice stream fronts retreated landward within their troughs at ~14.2 kyr BP[45], consistent with previous age constraints of ice retreat from the Baffin Island continental shelf[19,20,45]. The previous event of ice purge may have resulted in their episodic retreat in northeastern Baffin Island due to their destabilisation[25], whereas the initially unbuttressed CIS margin underwent a slower retreat. Furthermore, ice retreat in Lancaster Sound and Smith Sound led to the increased delivery of IRD-rich carbonates and deposition of BBDC-1 in Baffin Bay[15,45,56-58,60].

Conclusion

Identifying landforms associated with modern ice shelves remains a challenge due to their scarcity, the difficulty to access sub-ice-shelf environments and technological limitations of sonar imaging systems. However, the last decades witnessed improvements in ship-bound technologies (i.e., high-resolution multibeam echosounder, autonomous underwater vehicle and 2D/3D seismic imagery) allowing the identification of submarine bedforms diagnostic of past ice shelves, such as sub-ice-shelf keel scours/mega scale glacial lineations[41-43], GZWs[42] and corrugation ridges[44]. A more comprehensive understanding of such landforms is of particular interest as they provide direct and key evidence for past ice shelves in the Arctic, which may have considerable implications on glacial dynamics at the margin of continental ice sheets that was so far little studied.

The ice shelf scenario in northern Baffin Bay provides a satisfactory explanation for the landforms observed along the continental slope between Scott and Clyde troughs, as well as in Lancaster and Smith sounds. It is also in agreement with sediment assemblages identified on the continental slopes off Baffin Island and Greenland, as well as in Baffin Bay itself during the LGM. With a surface of at least 150 000 km^2 –an area comparable to some of the largest ice shelves of present-day Antarctica– the NBBIS constitutes an analogue from the past for understanding future changes to the cryosphere in a warming world in a context of disintegration of buttressing ice shelves. The demise of the NBBIS would have provided an ideal setting for triggering the acceleration of ice streams and the rapid loss of glacial ice to the ocean, thereby influencing drastically the ice flow regimes of the LIS, IIS and GrIS. These findings could further support the hypothesis that the North America High Arctic ice sheets did not have considerable contribution to rising sea level before Meltwater Pulse 1A[83,84]. Defining the extent of the NBBIS and the chronology of its history is, however, necessary for assessing a scenario that should include the acceleration of major Arctic ice streams following ice shelf collapse when identifying sources for Meltwater Pulse 1a. This paper provides the basis for further investigations aiming at documenting –both offshore and onshore– lateral ice shelf moraines of past ice shelves of the Arctic seas.

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Author contributions

POC conceived the study and initiated this project in cooperation with PL and JFG. POC interpreted the geophysical data sets, wrote the paper and prepared the figures. POC, PL, JFG, BD, CG, DH, and EB were involved in the discussion of the data and contributed to the final version of this paper.

Competing interests

The authors declare no competing interests.

Methods

Geophysical data along the Baffin Island continental slope

Swath bathymetric data was collected in 2017 during expedition MSM66 of the RV Maria S. Merian[85] using a Kongsberg Simrad EM122 (12 kHz) system, which allowed the coverage of Clyde Trough. This dataset is complemented by swath bathymetric data from ArcticNet cruises collected during transits from 2003 to 2016 onboard the CCGS Amundsen, equipped with a Kongsberg Simrad EM302 (30 kHz). These datasets were processed for anomalous data points and artefacts removal using Caris Hips and Sips software and gridded at a 10 m cell-size resolution. They were then imported into ESRI ArcGIS software for geomorphological mapping and landforms identification. The International Bathymetric Chart of the Arctic Ocean (IBCAO) data[86], gridded at a 500 m cell-size resolution, was also used to show overall bathymetry of Baffin Bay and its adjacent shelves. Parasound profiles were acquired onboard the RV Maria S. Merian using a Teledyne-Reson Parasound DS P-70 (secondary low frequency ca. 4 kHz). The raw data were recorded into ASD and PS3 format and then converted into SEGY using ps32segy software of. Dr. Hanno Keil (University of Bremen). The shallow-acoustic profiles were then imported into the IHS Markit Kingdom software for processing and interpretation. Seismic lines 78029_AG_274_1516 and 80028_AG_RAYT_257_0200 were acquired by the Geological Survey of Canada during airgun surveys in 1978 and 1980, respectively. Extraction and interpretation were done using the LizardTech GeoViewer® software. Both acoustic and seismic data were then transferred into Adobe Illustrator® for figure production. Thicknesses and water depth were calculated using a velocity of 1500 m/s.

Sediment cores and chronology

Sediment cores were compiled from previous studies to describe the lithostratigraphy along the Baffin Island continental slope and in Baffin Bay. Jenner et al.[45] noted that cores 64PC, 61PC, 74PC and 77PC (all included in this study) typify the regional lithostratigraphy along the northeast Baffin margin from north to south. Additionally, core 73PC[45] was included in the compilation as it was located nearby Clyde Trough. Cores located directly in front of the Baffin Island troughs in which the LGM assemblages were mostly dominated by glacial debris-flows and turbidites we not included. Cores from Baffin Bay were selected to allow a north to south representativity and to avoid redundant information. In general, the lithofacies provided a good correlation between them on the basis of radiocarbon dating. For full description of the cores, readers are referred to the original publications - 16PC[57]; 34PC and 36PC[56]; 61PC, 64PC, 73PC, 74PC and 77PC[45]; 67PC[21]; SL174[60].

Radiocarbon ages were calibrated within the age-depth modelling process using the online software Calib 8.2 with the Marine20 radiocarbon age calibration curve[87] and a local reservoir correction (ΔR) of 87±20[88] commonly used on northeastern Baffin Island[26,45,57,60] (Supplementary Table 1). This reservoir correction is in line with the one currently used for radiocarbon date calibrations of central West Greenland[34,71], that indicate a reservoir correction (ΔR) of 140 ± 35 years[89]. We recognize that an offset caused by a well-mixed ocean was most likely variable through time and the appropriate ΔR reservoir correction for the region might have been larger than the one used and provide younger ages. However, this would not considerably change the interpretation of the ice shelf scenario.

Data availability

The swath bathymetric data collected in 2017 during expedition MSM66[85] have been deposited in the PANGAEA repository, available under https://doi.org/10.1594/PANGAEA.902341. The swath bathymetric data from ArcticNet cruises can be visualized on the Université Laval Géoindex + website (http://geoindex-plus.bibl.ulaval.ca). The Parasound profiles collected in 2017 during expedition MSM66[85] have been deposited in the PANGAEA repository, available under https://doi.pangaea.de/10.1594/PANGAEA.944843. The seismic reflection data along with the acquisition specifics are available on the Marine Data Holding public repository of National Resources Canada (http://geogratis.gc.ca/).

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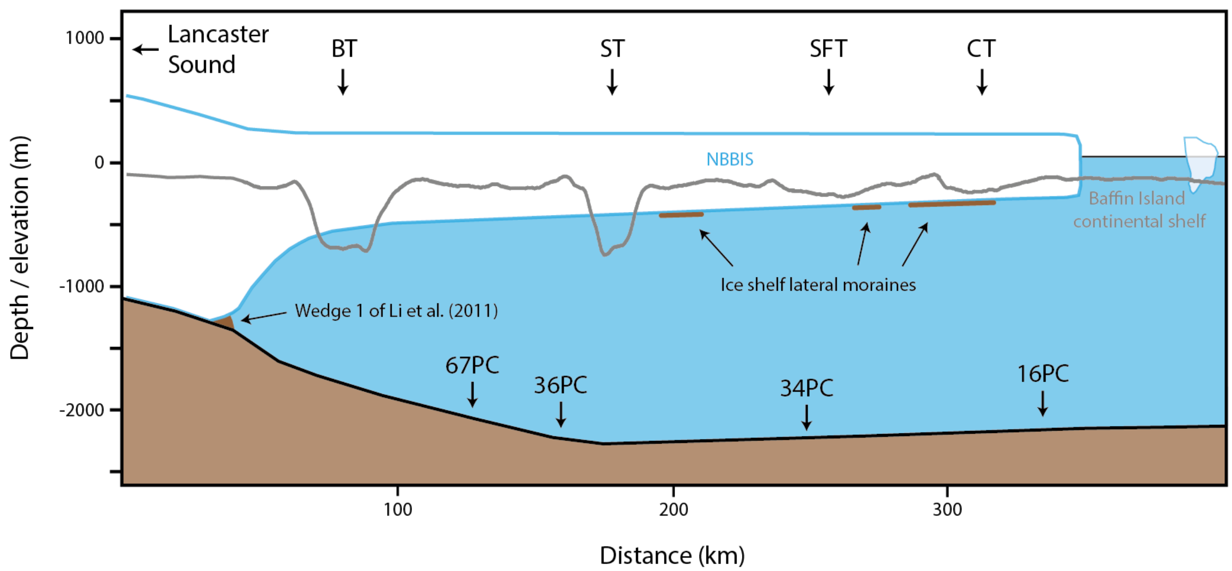
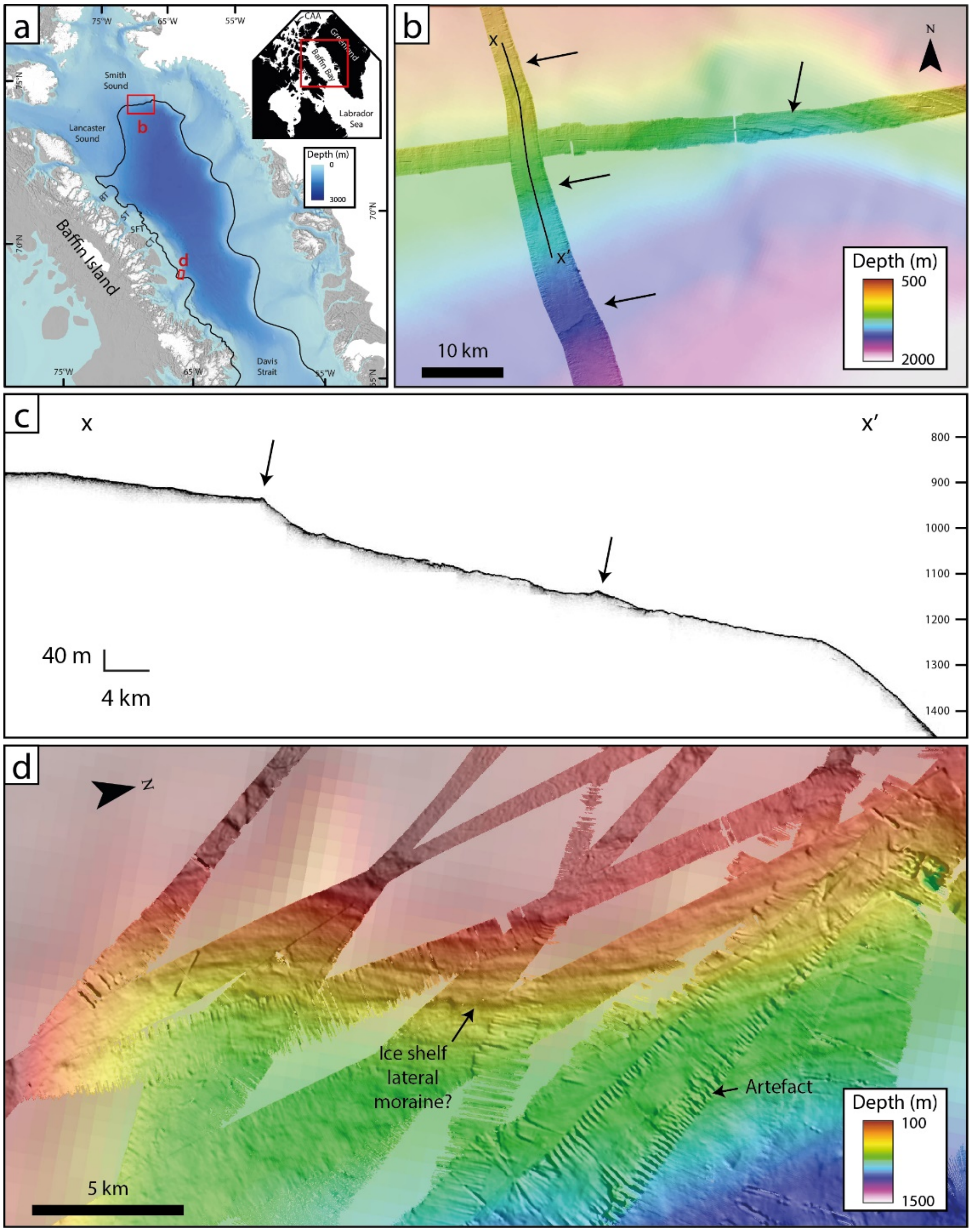
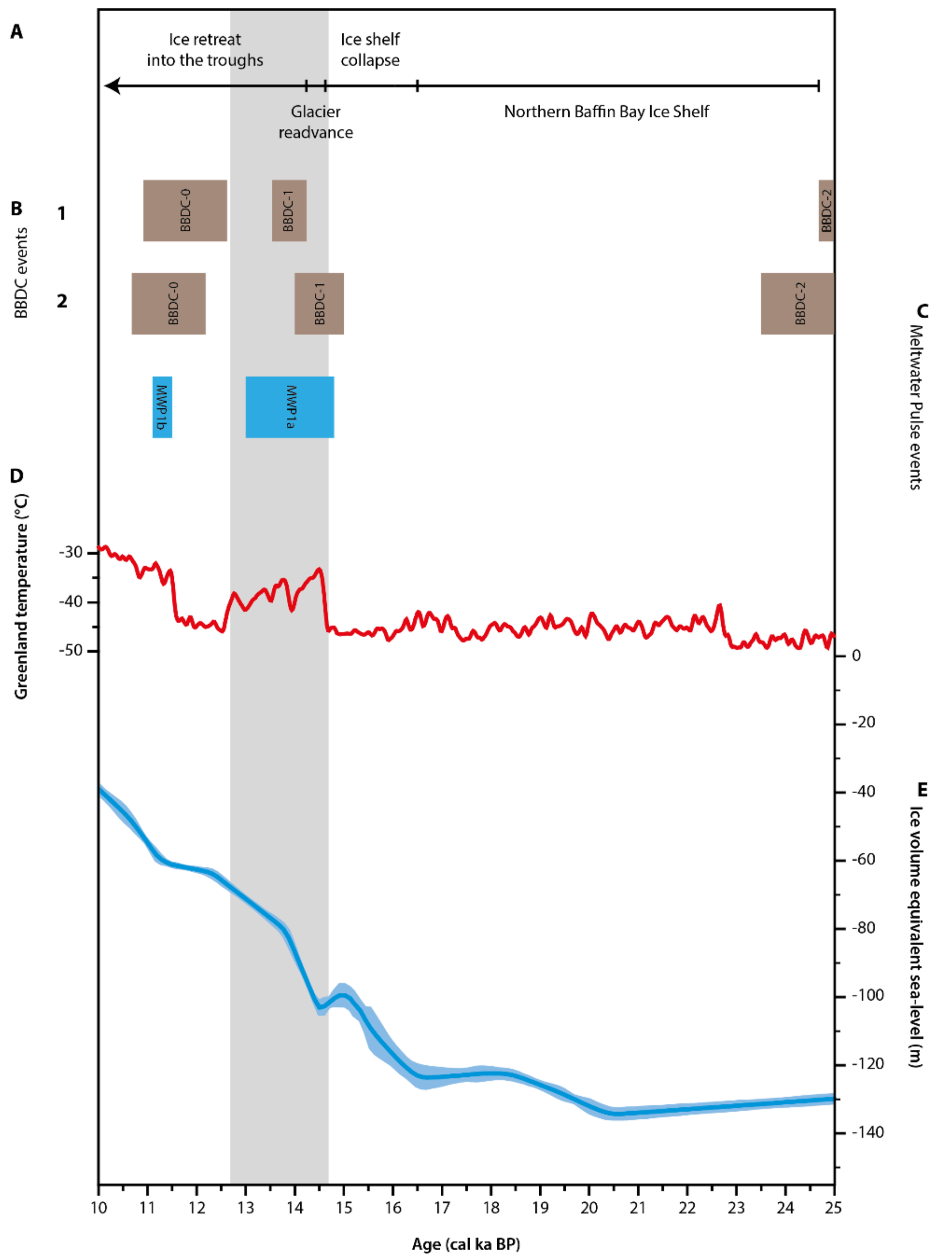


Supplementary Fig. 1: Longitudinal transect of the NBBIS in northern and central Baffin Bay. Location of the ice shelf lateral moraines discussed in this paper are in dark gray. Core locations in Baffin Bay are tentatively given. BT: Buchan Trough; ST: Scott Trough; SFT: Sam Ford Trough; CT: Clyde Trough.



Supplementary Fig. 2: Geomorphological evidence of the presence of an ice shelf in northern Baffin Bay. Arrows indicate GZWs and moraines. (a) Location of figure S2b cores and maximum extent of grounded ice on western Baffin Bay (thick line). (b) Bathymetry off Smith Sound showing GZWs between ~900 and ~1200 mbsl, and possibly a moraine at ~1700 mbsl. (c) Chirp profile in Smith Sound showing the two GZWs at ~900 and ~1200 mbsl. (d) Bathymetry off Home Bay showing a potential ice shelf lateral moraine at ~400 mbsl.



Supplementary Fig. 3: Chronology of the last deglaciation in Baffin Bay and regional climatic events. (a) Baffin Bay Ice Shelf history. (b) Baffin Bay Detrital Carbonate layers based on radiocarbon dating[57,60] (1) and relative paleointensity (RPI) chronology[59] (2). (c) Meltwater Pulse events[84]. (d) Greenland mean-annual temperatures reconstructed using $\delta^{15}N$ gas-phase[81] (red line). (e) Ice volume equivalent sea-level[80] (blue line) presented with one standard-deviation. The grey shaded area represents the Bølling–Allerød warm interval.

Supplementary Table 1: Radiocarbon ages for cores used in this study.

Sample information		**Conventional radiocarbon age**		**Calibrated radiocarbon ages yrs BP (2σ)**			**Reference**
Core	Depth in core	^{14}C age years BP	±	Minimum	Maximum	Median	
16PC	66	11 905	40	12980	13302	13141	*Simon et al., 2012*
	79	12 470	40	13573	13980	13752	
	111	13 820	130	15324	16134	15737	
34PC	37	12 380	105	13374	13976	13650	*Andrews et al., 1998*
64PC	135	9200	35	9484	9852	9639	*Jenner et al., 2018*
	275	13 850	95	15443	16111	15777	
	330	12 500	45	13596	14002	13796	
73PC	123	19 900	80	22621	23192	22921	*Jenner et al., 2018*
77PC	137	10 550	40	11 270	11 736	11 504	*Jenner et al., 2018*
	200	12 750	55	13 867	14 442	14 137	
	638	37 900	1 600	38 410	41 213	43 542	
SL174	97	9793	120	10 122	10 859	10 456	*Jackson et al., 2017*
	122	10 390	40	11 104	11 495	11 276	
	142	10 997	110	11 831	12 553	12 202	
	169	11 010	85	11 888	12 515	12 226	
	196	11 410	50	12 506	12 817	12 673	
	215	12 000	80	13 038	13 455	13 234	
	233	12 580	60	13 656	14 111	13 895	
	278	14 510	120	16 256	16 990	16 629	
	294	15 060	110	16 963	17 698	17 294	

Ages were calibrated within the age-depth modelling process, using the online software Calib 8.2 with the Marine20 radiocarbon age calibration curve[87]. A local reservoir correction (ΔR) of 87±20 was used to account for the regional offset of the world ocean 14C age[88].