Summary and outlook

The account of the onset and subsequent, repeated glaciations of Greenland, and the Disko Bugt region in particular, leaves more questions than answers. However, the detailed investigations of recent decades support the old idea that the preglacial, major fluvial drainage pattern of central Greenland was westwards towards the Disko Bugt region. The subsequent drainage of the Greenland ice sheet since its formation and during repeated glaciations was also predominantly westwards, and at the maximum extent of the Inland Ice, major ice streams in the present offshore region occupied and modified former river valleys and fjords.

The onset and extent of the early glaciations are still not clear. They must, however, have had characteristics similar to the glaciation of the present Antarctic or to high-arctic ice shelves, in that they showed a high sensitivity to climatic and eustatic sea-level changes and perhaps included ice streams of different character from those that drain the Inland Ice today. During the Illinoian, the glacial limit of the ice sheet may have been located at Store Hellefiskebanke and at the central part of Disko Banke. During the Wisconsinan, the ice margin may have extended only to the eastern part of Store Hellefiskebanke. On both occasions, the outer Egedesminde Dyb was probably occupied by a high-arctic type 'ice stream', but data to support this scenario are so far lacking.

A number of interglacial and interstadial deposits have been discovered along the outer coast of Disko island, and farther north at other localities along the extreme western parts along the outer coast. These have been referred to a number of marine events, but the extent of the ice sheet during and between the events is unknown. Modelling indicates, however, that during the last interglacial, the Eemian or Sangamonian, the Inland Ice was reduced to a degree where it was almost separated into a southern and northern ice sheet (Fig. 14).

The extent of the ice sheet during the last glacial maximum at 21 ka B.P. is still not established, neither from offshore stratigraphy nor from dates from marine sediment cores. It is likely that the pronounced warming at 14.7 ka B.P., combined with an initial rise of global sea level, caused a recession of the ice margin. During the cold interval of the Younger Dryas, the ice margin may have been located at the marked basalt escarpment that forms a submarine barrier, which would mean that the marine ice margin was situated at a depth of only 300–400 m.

In spite of the depth of this barrier, it must have had a blocking effect on ice movement, so that the large piedmont glacier that filled Disko Bugt during and immediately after the Younger Dryas was thinning rather than receding. In contrast, the few radiocarbon dates from Vaigat, north of Disko, provide minimum dates for the last deglaciation suggesting that the outlet here underwent gradual recession from 12.4 to 10.3 ka B.P. (Fig. 22).

The role of the inner part of Egedesminde Dyb, which has depths in excess of 1000 m, is unclear. The available descriptions and sea charts do not reveal a regular, U-formed conduit, but the western, steep basalt wall shows characteristics indicative of glacial plucking. We suggest that it was only the site of a major ice stream that helped to drain Disko Bugt during the initial thinning of the ice cover for a short time interval around 10.5–10 ka B.P.

It is certain that by *c.* 10 ka B.P. a major break-up of the Disko Bugt ice cover had taken place, and this probably occurred very rapidly, over a century or less. It is presumed that the change from the large, marine-based piedmont ice lobe to a land-based ice margin, with consequent changes in geometry, resulted in the prolonged halt or slowdown of ice-margin recession in the central parts of Disko Bugt that lasted from *c.* 9.9 to *c.* 7.9 ka B.P. As long as the front was situated close to Isfjeldsbanken near Ilulissat, the calf-ice production of Jakobshavn Isbræ was probably much reduced. The cold event around 8.2 ka B.P. may also have contributed to the low recession rate.

Developments were different in the northern part of Disko Bugt, where the Torsukattak icefjord, the eastern continuation of the Vaigat strait, experienced a more continuous recession that brought the ice margin close to its present position before 8 ka B.P. However, the presence of moraines indicates minor deceleration or halts in the recession, perhaps at pinning points.

An iceberg bank similar to that near Ilulissat occurs at the junction between the Torsukattak icefjord and the Vaigat strait. The ice margin was presumably situated here from around 9.9 ka B.P., contemporaneous with the initial ice-margin position at the Jakobshavn iceberg bank. However, the ice margin was only situated at the mouth of Torsukattak icefjord for a short time, and also had a reduced frontal area. The relatively deep fjord may have favoured the continuous recession.

Around Jakobshavn Isbræ, the ice margin receded to its present location somewhat later, with 6.1 ka B.P. as a minimum age; recession of the ice-sheet margin continued to the east during the Holocene thermal maximum. Large undocumented fluctuations of Jakobshavn Isbræ may have occurred during the Neoglacial. We suggest that the high calf-ice production of Jakobshavn Isbræ began after the initial recession from Isfjeldsbanken, after *c.* 8 ka B.P. After the subsequent recession, at 5–4 ka B.P., the frontal position was at least 15–20 km east of the present location.

South of Disko Bugt, a relatively fast recession over the lowlands ended with the ice margin receding to its present position probably as early as 8 ka B.P. In this region, recession of the ice margin also continued beyond (east of) the present location. The extent of marine deposits in this region points to a partially marine ice margin during most of the recession. The depths of the fjords in this region, as far as is known, do not indicate the presence of troughs that could support major ice streams during the recession.

Ice streams are normally located in the ablation area of the ice sheet over Greenland, at sites where sufficiently deep troughs in the subsurface can act as conduits for the ice streams. With the gradual recession of the ice margin during the Wisconsinan to Holocene transition, periodic formation of ice streams might be expected during recession. The temporary role of such ice streams with respect to the total mass balance of the ice-sheet sector draining into the Disko Bugt region has still to be evaluated. Detailed mapping of the entire subsurface beneath the ice margin is essential in constructing the history of development of the ice sectors of the Disko Bugt region. If a prerequisite for the development of an ice stream is that it is located in a deep conduit in the marginal areas of the ice sheet, the life of Jakobshavn Isbræ with its present activity may be restricted to the Holocene period since *c.* 8 ka B.P.

The subsequent Little Ice Age readvance culminated in the area around Jakobshavn Isbræ with a major readvance in the middle and late 19th century. The extent of this readvance is unknown for the surrounding areas, with the exception of the Paakitsoq area. Historical information for the 20th century shows a marked recession only around Jakobshavn Isbræ, whereas the other ice-sheet sectors draining to Disko Bugt show a quasi-stability or even a tendency to advance over this period.

During the Holocene thermal maximum and the subsequent cooling, Jakobshavn Isbræ controlled much of the ice drainage of central West Greenland, and its marked sensitivity to temperature changes must be linked to ablation and sliding mechanisms at the base of the ice-sheet margin. In general, Disko Bugt has played an important role for ice drainage of the central western slope of the ice sheet since the Wisconsinan. However, the role of individual factors such as ice streams, general ablation and related subglacial meltwater transfer to the bottom of the ice and marine versus land-based ice margin, still needs to be quantified. This can be achieved through better mass-balance investigations and dynamic modelling of the ice-margin change through time. Furthermore, the role of the individual troughs in Disko Bugt and offshore as conduits for the ice should be considered. The scattered positions of these troughs, and their relationship to temporary halts of the ice margin, point to a shift in the nature and position of ice streams during the recession of the ice margin since the last glacial maximum. Whether these offshore troughs had the same central role as the present ice stream of Jakobshavn Isbræ during the recession is still to be documented.

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Appendix 1

Index to Greenland place names

Names in quotation marks are informal names. Unless stated otherwise, the localities are in West Greenland.

Aasiaat (Egedesminde)	town
Akuliarutsip Sermersua (Nordenskiöld Gletscher)	glacier
Akulliit	island
Alanngorliup Sermia	glacier
Alluttoq (Arveprinsen Ejland)	island
Ammassalik (Tasiilaq)	town, East Greenland
Arfersiorfik	fjord
Arveprinsen Ejland (Alluttoq)	island
Buksefjorden (Kangerluarsunnguaq)	fjord
Camp Century	former ice-sheet station
Christianshåb (Qasigiannguit)	town
Claushavn (Ilimanaq)	town
Disko (Qeqertarsuaq)	island
Disko Banke	shallow offshore area
Disko Bugt (Qeqertarsuup Tunua)	bay
Disko Fjord (Kangerluk)	fjord
Dye 3	former ice-sheet station
Egedesminde (Aasiaat)	town
Egedesminde Dyb	submarine trough
Eqalorutsit Killiit Sermiat	glacier
Eqaluit (Laksebugt)	bay
Eqip Sermia	glacier
Gade Gletscher	glacier
Godhavn (Qeqertarsuaq)	town
Godthåb, (Nuuk)	capital of Greenland
Gunnbjørn Fjeld	mountain, East Greenland
Harald Moltke Bræ (Ullip Sermia)	glacier
Hareøen (Qeqertarsuatsiaq)	island
Helheimgletscher	glacier, East Greenland
Hellefisk-1	offshore well
Ikerasaap Sullua (Qarajaq Isfjord)	icefjord
Ilimanaq (Claushavn)	town
Ilulissat (Jakobshavn)	town
Ilulissat Icefjord	icefjord (world heritage site)
Inland Ice	Greenland icecap
Innaarsuit	land area
Isfjeldsbanken	submarine threshold
Jakobshavn (Ilulissat)	town
Jakobshavn Isfjord (Kangia)	icefjord
Jakobshavn Isbræ (Sermeq Kujalleq)	glacier
Jøkelbugten	bay
Kane Basin	large bay (basin)
Kangerluarsuk (Vaskebugt)	bay
Kangerluarsunnguaq (Buksefjorden)	fjord
Kangerlussuaq (Søndre Strømfjord)	fjord/airport
Kangerlussuaq	fjord, East Greenland
Kangerlussuaq	branch of Uummannaq Fjord
Kangerlussuaq Gletscher	glacier, East Greenland
Kangersooq (Nordfjord)	fjord
Kangersuneq	fjord
Kangia (Jakobshavn Isfjord)	icefjord
Kangilerngata Sermia	glacier
Kangilliup Sermia (Rink Isbræ)	glacier
Kap Farvel (Nunap Isua)	cape
Laksebugt (Eqaluit)	bay
‘Lerbugten’	bay
Lersletten (Naternaq)	clay plain
‘Lersletten’ (Narsarsuaq)	clay plain
Marraq	clay plain
Melville Bugt (Qimusseriarsuaq)	bay
Nanortalik	town
Narsap Sermia	glacier
Narsarsuaq (‘Lersletten’) at Ilimanaq	clay plain
Narsarsuaq	airport, South Greenland
Naternaq (Lersletten)	clay plain
Nordenskiöld Gletscher (Akuliarutsip Sermersua)	glacier
NorthGRIP	ice-core site
Nordfjord (Kangersooq) at Disko island	fjord
Nuuk	peninsula
Nuuk (Godthåb)	capital of Greenland
Nuussuaq	peninsula

Oqaatsut (Rodebay)	settlement
Orpissooq	fjord
Paakitsoq	bay
Paamiut (Frederikshåb)	town
Pattorfik	coastal stretch
Peary Land	region, North Greenland
Pinguarsuit	rock knoll
Pituffik (Thule Air Base)	airbase
Qajaa	ruin site
Qapiarfiit	land area
Qaqortoq (Julianehåb)	town
Qarajaq Isfjord (Ikerasaap Sullua)	icefjord
Qasigiannguit (Christianshåb)	town
‘Qarsortoq’	coastal cliff
Qeqertarsuaq (Disko)	island
Qeqertarsuaq (Godhavn)	town
Qeqertarsuatsiaq (Hareøen)	island
Qeqertarsuatsiaq	island south of Aasiaat
Qeqertarsuup Tunua (Disko Bugt)	bay
Qilertinnguit	mountain
Rink Isbræ (Kangilliup Sermia)	glacier
Rodebay (Oqaatsut)	settlement
‘**S**andbugten’	bay
Sanddalen	valley
Saqqarliup Sermia	glacier
Serfarsuit	headland, Kangersuneq Fjord
Sermeq (Upernavik Isstrøm)	glacier
Sermeq Avannarleq in Kangia	glacier
Sermeq Avannarleq in Torsukattak	glacier
Sermeq Kujalleq (Jakobshavn Isbræ)	glacier
Sermeq Kujalleq in Torsukattak	glacier
Sermeq Kujalleq (Store Gletscher) in Qarajaq icefjord	glacier
Sermermiut	bay/ruin site
Sigguup Nunaa (Svartenhuk Halvø)	peninsula
Sikuiuitsoq near Ilulissat	fjord
Sisimiut (Holsteinsborg)	town
Søndre Strømfjord (Kangerlussuaq)	fjord/airport
Store Gletscher (Sermeq Kujalleq in Qarajaq icefjord)	glacier
Store Hellefiskebanke	shallow offshore area
Storstrømmen	glacier
Sullorsuaq (Vaigat)	strait
Summit	ice-sheet station
Svartenhuk Halvø (Sigguup Nunaa)	peninsula
Swiss Station	ice-sheet station
Tasiusaq	fjord
Thule Air Base (Pituffik)	airbase
Tininnilik	ice-dammed lake
Tissarissoq	former part of ice-sheet margin
Torsukattak	icefjord
Tuapaat	coastal stretch
Upernavik	town
Upernavik Isstrøm (Sermeq)	glacier
Ussuit	bay
Uummannap Kangerlua (Uummannaq Fjord)	fjord
Uummannaq Fjord (Uummannap Kangerlua)	fjord
Vaigat (Sullorsuaq)	strait
Vaskebugt (Kangerluarsuk)	fjord

Appendix 2

Radiocarbon analyses

New radiocarbon ages reported in Tables 3 and 4 were determined by accelerator mass spectrometry (AMS). Dating was performed at the Ångström Laboratory at Uppsala, Sweden, under the supervision of Göran Possnert. The outer part of the shell material was removed by hydrochloric acid (HCl) to prevent contamination. The ages are reported in conventional radiocarbon years B.P. (before present = A.D. 1950). The dates have been corrected for isotopic fractionation by normalising to a $\delta^{13}C$ value of –25‰ on the PDB scale. The $\delta^{13}C$ measurements were performed on a conventional mass spectrometer. The dates have been corrected for a seawater reservoir effect by using an apparent age of 400 years (Bennike 1997). The reservoir-corrected ages have been calibrated into calendar years before present (= A.D. 1950) using the INTCAL04 dataset and the OxCal version 3.10 software program (Bronk Ramsey 2001).

With respect to previous radiocarbon age determinations, compiled in Tables 2–4, those marked AAR and AA were also determined by accelerator mass spectrometry, whereas the other analyses were carried out by conventional methods. Older dates on marine material have been reservoir corrected by subtracting 400 years (laboratory codes AAR, AA) or no corrections were applied (laboratory codes I, K, Hel). The latter dates have been corrected for isotopic fractionation by normalising to a $\delta^{13}C$ value of 0‰ on the PDB scale, or no correction for isotopic fractionation was applied. These dates have a 'built-in' correction.