GEOLOGICAL SURVEY OF DENMARK AND GREENLAND BULLETIN 27 • 2012

Neoglacial and historical glacier changes around Kangersuneq fjord in southern West Greenland

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

Geological Survey of Denmark and Greenland Bulletin 27

Keywords
Greenland, Godthåbsfjord, Kangersuneq, Kangiata Nunaata Sermia, glaciology, tidewater glaciers, Quaternary, Holocene, Neoglacial, Little Ice Age.

Cover
The calving front of Kangiata Nunaata Sermia seen from the south-west. The trimline zone on Nunataarsuk semi-nunatak in the background reaches almost to the top of the mountains. The calving front is 4.5 km long. Photograph: Dirk van As, 22 August 2011.

Frontispiece: facing page
Qamanaarsuup Sermia is separated into an upper and a lower part by a bedrock high. The area in the foreground was covered by an ice-dammed lake during the Little Ice Age maximum. The lower part of the glacier is *c.* 2 km wide. Photograph: Dirk van As, 28 August 2012.

Scientific editor of this volume: Jon R. Ineson
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Illustrations: Jette Halskov
Digital photographic work: Benny M. Schark
Layout and graphic production: Kristian A. Rasmussen
Printers: Rosendahls - Schultz Grafisk A/S, Albertslund, Denmark
Manuscript received: 31 January 2012
Final version approved: 24 August 2012
Printed: 27 December 2012

ISSN 1604-8156
ISBN 978-87-7871-347-6

Citation of the name of this series
It is recommended that the name of this series is cited in full, viz. *Geological Survey of Denmark and Greenland Bulletin.*
If abbreviation of this volume is necessary, the following form is suggested: *Geol. Surv. Den. Green. Bull.* 27, 68 pp.

Available from
Geological Survey of Denmark and Greenland (GEUS)
Øster Voldgade 10, DK-1350 Copenhagen K, Denmark
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Contents

Abstract

Weidick, A., Bennike, O., Citterio, M. & Nørgaard-Pedersen, N. 2012: Neoglacial and historical glacier changes around Kangersuneq fjord in southern West Greenland. *Geological Survey of Denmark and Greenland Bulletin* 27, 68 pp.

The Nuup Kangerlua region in southern West Greenland became deglaciated in the early Holocene and by the mid-Holocene, the margin of the Inland Ice was located east of its present position. Discussion of late Holocene changes in the frontal positions of outlets relies on descriptions, paintings, photographs, maps, data from investigations of Norse ruins, aerial photographs and satellite images.

The Kangiata Nunaata Sermia glacier system has receded over 20 km during the last two centuries, indicating a marked response to climatic fluctuations during and since the Little Ice Age (LIA). A large advance between 1700 and 1800 was followed by rapid recession in the first half of the 1800s. Limited data from *c.* 1850–1920 indicate that although the long-term position of the glacier front remained *c.* 10–12 km behind the LIA maximum, the late 1800s and the early 1900s may have seen a recession followed by an advance that resulted in a pronounced moraine system. The ice-dammed lake Isvand formed during the LIA maximum when meltwater from the western side of Kangiata Nunaata Sermia drained to the Ameralla fjord in the west. This is in contrast to the drainage pattern before the 1700s, when water probably drained to Kangersuneq in the north. Thinning of Kangiata Nunaata Sermia resulted in total drainage of Isvand between 2000 and 2010 and the discharge of water through Austmannadalen has now returned to the same level as that in medieval times.

Other outlets in the region, such as Akullersuup Sermia and Qamanaarsuup Sermia have varied in phase with Kangiata Nunaata Sermia, but with amplitudes of only a few kilometres. In contrast, Narsap Sermia has been nearly stationary and Kangilinnguata Sermia may have advanced until the middle of the 1900s.

Lowland marine outlets in south-western Greenland were characterised by large amplitude changes during the Neoglacial. Extreme examples, in addition to Kangiata Nunaata Sermia, are Eqalorutsit Killiit Sermiat at the head of Nordre Sermilik fjord in southern Greenland and Jakobshavn Isbræ in Disko Bugt, central West Greenland. The Neoglacial advances appear to have occurred at different times, although this may in part reflect the limited information about fluctuations prior to the 1930s. The differences could also reflect variations in mass balance of different sectors of the ice sheet, different subglacial dynamics or topographical factors. The lowland areas are separated by uplands and highlands that extend below the marginal part of the Inland Ice; in such areas, the outlets have been advancing almost up to the present, so that the position of the glacier front around AD 2000 broadly coincides with the LIA maximum. Charting the fluctuations of the outlets thus illustrates the large variability of the glaciers' response to changing climate but it is notable that the number of advancing outlets has decreased markedly in recent years.

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Introduction

In recent years, the Greenland ice sheet (the Inland Ice) has become a symbol of climate change. The ice sheet is losing mass at an accelerating rate (Dahl-Jensen *et al.* 2009; Rignot *et al.* 2011; van As *et al.* 2011), and it is becoming increasingly clear that we need a better understanding of the past behaviour of the ice sheet and in particular its sensitivity to climatic change. Here we present a review of our current knowledge about late Holocene changes of the Inland Ice margin in the Nuup Kangerlua region in southern West Greenland (Figs 1, 2).

Recent climate change has resulted in thinning of marginal parts of the Inland Ice (Dahl-Jensen *et al.* 2009). Politicians as well as ordinary citizens are concerned that the melting of the Inland Ice and the consequent rise in sea level will lead to world-wide environmental and sociological problems. Over the next century, the sea level may rise by about 1 m; a large part of this predicted rise is attributed to melting of the Inland Ice.

However, during the past centuries different sectors of the margin of the Inland Ice have responded to climate change in various ways. Some sectors have been stable, others have receded and others have advanced. This implies that predicting glacier hazards such as changes in calf-ice production from the large tide-water outlets or ice-margin changes at hydropower plants can be difficult.

It must be remembered that the Inland Ice is an immense body of ice. At the margin, the ice sheet is often confluent with minor ice caps or other local glaciers that have their own mass budget. The Inland Ice has extensive accumulation areas, and it is difficult to delimit the catchment areas for the individual sectors or outlets from the ice sheet. In addition, the catchment areas may change over time. The aim of this work is to compile information about marginal changes of the Inland Ice in the Nuup Kangerlua region to give an impression of former variations. The work focuses on the last centuries, but includes data concerning the last 6000 years.

Nuup Kangerlua (Godthåbsfjord) is the largest fjord complex in southern West Greenland and the longest fjord extends *c.* 160 km. The fjord branches are often surrounded by steep mountains, but lowlands are also represented. The inner parts of Nuup Kangerlua were colonised by Norse people about 1000 years ago. The Norse established the Western Settlement (Vesterbygd) with *c.* 95 farms and two churches, but they abandoned the region after 350–400 years (Arneborg 2004; Dugmore *et al.* 2012). The only written information about the Greenland ice sheet from the Norse period is found in *The King's mirror* from *c.* 1260 where it is briefly stated that most of the land is icebound (Larson 1917; Weidick & Bennike 2007). Some legends from the later Eskimo people (Thule culture) refer to their relationships with the Norse people (e.g. accounts by Aron from Kangeq and Jens Rosing presented in Birket-Smith 1961), but provide no information on glacier extent or glacier changes. The European exploration of the Baffin Bay and Davis Strait

Fig. 1. Map of Greenland showing the location of the studied region and the location of selected ice cores.

region from *c.* 1500–1700 did not increase our knowledge of the Greenland ice sheet or glaciers in Greenland. The region was again colonised by Europeans in 1721, and from this time onward a fairly rich body of historical information exists about the outlet glaciers from the Inland Ice in the region.

This presentation summarises information about glacier changes from geological observations, archaeological evidence, historical sources, as well as more recent evidence from aerial photographs and satellite images. An index of relevant place names is included to aid understanding of older data sources. The emphasis is on the scattered historical information on glaciers, which dates back to the early part of the exploration history in the beginning of the 1700s, and up to the first half of the 1900s. Work on the fluctuations of the glaciers in this area was initiated 52 years ago (Weidick 1959); more recent work and the recognition or re-evaluation of historical sources have necessitated an updating and revision of the record.

Since the advent of aerial photography in the 1930s and particularly with the recent influx of satellite information, data on ice-sheet history have become both more accurate and more readily available. These data are dealt with in more general terms, tracing the major trends of the glacier fluctuations up to the first decade of this century.

Setting

This study is centred on the area at the head of Nuup Kangerlua (Godthåbsfjord), *c.* 80 km east of the town of Nuuk (Fig. 3). The ice-free land in this part of Greenland is 100–125 km wide, with lowlands and uplands with elevations up to 1000–1500 m above sea level (a.s.l.). The landscape is dissected by numerous straits and fjords, of which the longest, Nuup Kangerlua, reaches from the outer coast to the Inland Ice. In its inner part, in the Kangersuneq area, the ice-sheet margin reaches sea level, or close to sea level, in five outlets. From south to north, these are Kangiata Nunaata Sermia, Akullersuup Sermia, Qamanaarsuup Sermia, Narsap Sermia and Kangilinnguata Sermia (Figs 2, 3).

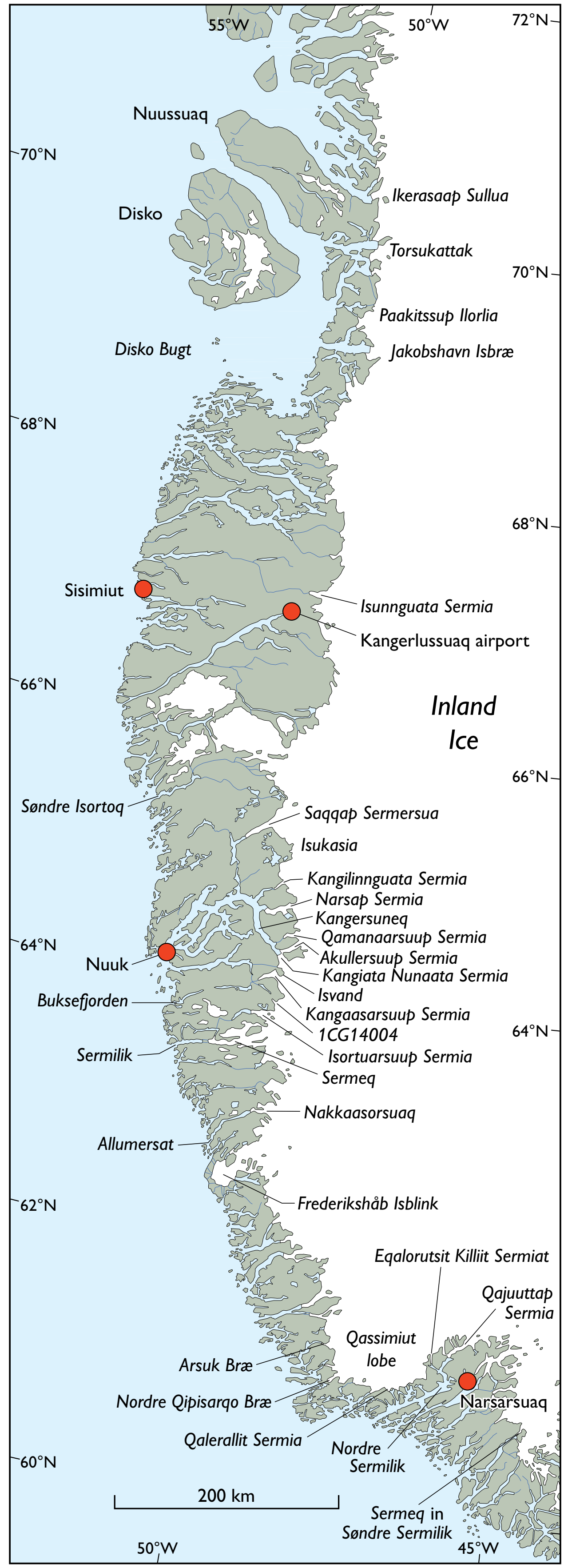
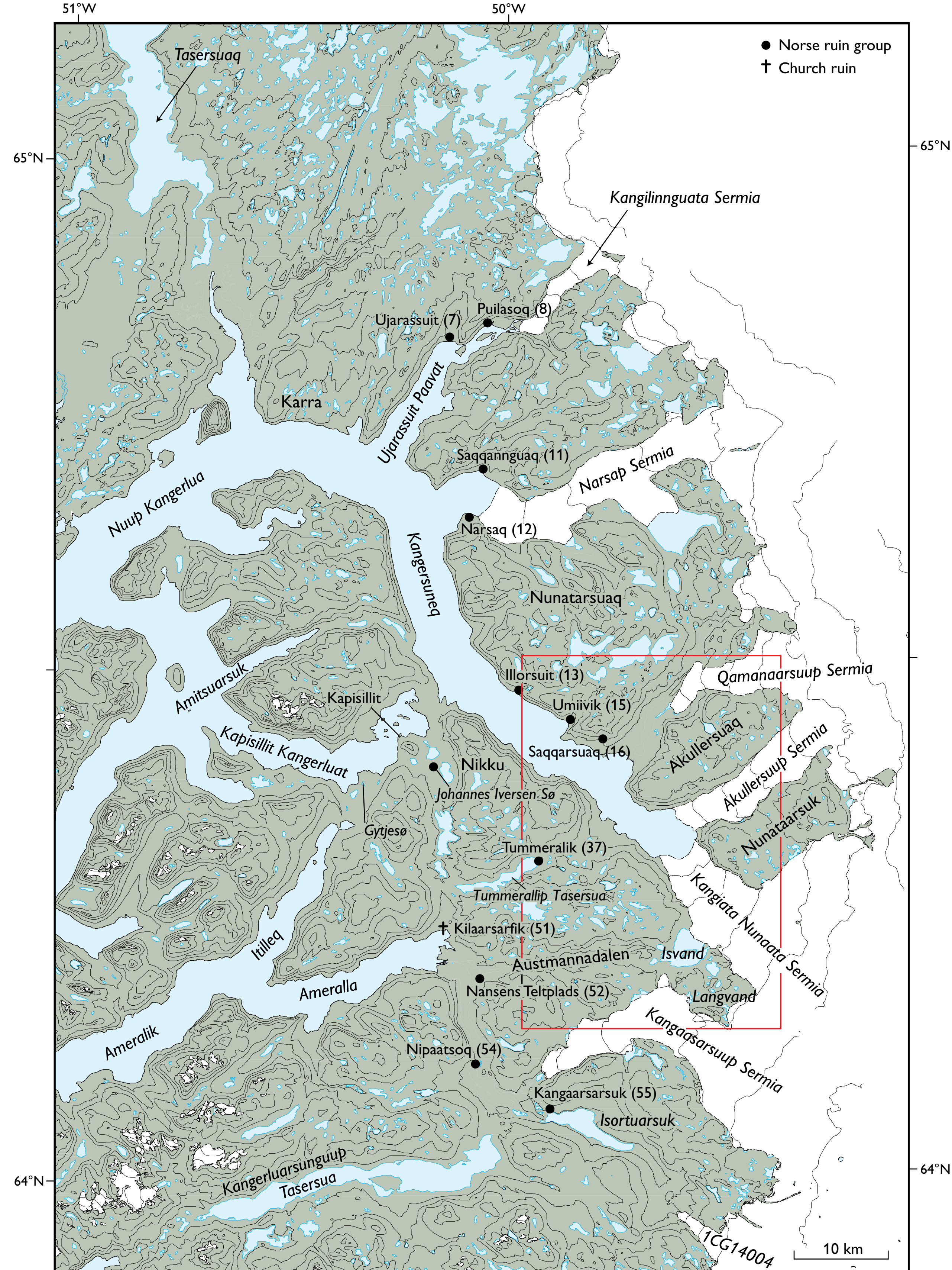


Fig. 2. Map of south-western Greenland showing outlet glaciers, the marginal areas of the Inland Ice and major fjords mentioned in the text.



51°W
50°W
65°N
64°N
Norse ruin group
Church ruin
Tasersuaq
Kangilinnguata Sermia
Puilasoq (8)
Ujarassuit (7)
Karra
Ujarassuit Paavat
Saqqannguaq (11)
Narsap Sermia
Nuup Kangerlua
Narsaq (12)
Kangersuneq
Nunatarsuaq
Illorsuit (13)
Qamanaarsuup Sermia
Amitsuarsuk
Kapisillit
Umiivik (15)
Saqqarsuaq (16)
Akullersuaq
Akullersuup Sermia
Kapisillit Kangerluat
Nikku
Johannes Iversen Sø
Nunataarsuk
Gytjesø
Tummeralik (37)
Tummerallip Tasersua
Kangiata Nunaata Sermia
Kilaarsarfik (51)
Itilleq
Austmannadalen
Isvand
Nansens Teltplads (52)
Langvand
Ameralla
Ameralik
Kangaasarsuup Sermia
Nipaatsoq (54)
Kangaarsarsuk (55)
Isortuarsuk
Kangerluarsunguup
Tasersua
1CG14004
10 km

Kangiata Nunaata Sermia and Akullersuup Sermia are both calving tidewater glaciers with appreciable calf-ice production. The flux of Kangiata Nunaata Sermia was *c.* 6 km^3 per year in 1996, but by 2005 it had increased by 33% (Rignot & Kanagaratnam 2006). According to Mortensen *et al.* (2011), the glacial ice discharge is 8 km^3 per year. At their maximum extent, the two glaciers Kangiata Nunaata Sermia and Akullersuup Sermia were coalescent, and the calving front of the glacier system was located more than 20 km farther to the north than today. The term 'Kangiata Nunaata Sermia glacier system' is used here to describe the two confluent glaciers.

The third glacier, Qamanaarsuup Sermia ends on land today, but previously ended in a proglacial lake that was dammed by the advanced, confluent glacier system consisting of the present-day Kangiata Nunaata Sermia and Akullersuup Sermia.

The fourth glacier, Narsap Sermia, is also a tidewater glacier, but calf-ice production is small, and it is sometimes possible to sail along the glacier front by boat. The fifth outlet glacier, Kangilinnguata Sermia, is situated at the head of Ujarassuit Paavat, which is a northern branch of Kangersuneq fjord at the head of Nuup Kangerlua. Kangilinnguata Sermia is presently a minor land-based outlet.

Whereas Kangiata Nunaata Sermia, Akullersuup Sermia and Qamanaarsup Sermia were surrounded by broad, fresh trimline zones in the last century, such a zone is only found to a very restricted degree around Narsap Sermia. The trimline zone around Kangilinnguata Sermia is narrow, which indicates a slight recession of the glacier in recent times. Kangaasarsuup Sermia, south of Kangiata Nunaata Sermia, has experienced a somewhat larger glacier recession (Fig. 4).

Mass-balance measurements have been carried out on Qamanaarsup Sermia between 1979 and 1989 and on a small local nameless glacier (1CG14033) situated at the junction between Ameralik fjord and Kangerluarsunnguaq (Buksefjorden), *c.* 75 km south-west of Qamanaarsuup Sermia, during the period 1982–1989 (Braithwaite 1989, 1990; Braithwaite & Olesen 1989). At both places, the investigations were carried out to evaluate the hydropower potential in the region. On Qamanaarsuup Sermia, volume changes were also measured from 1968 to 1980 (Knudsen 1983) and again from 1988 to 1993 (Taurisano 2004). North of the Kangersuneq area (at Isukasia), glaciological investigations were conducted in connection with evaluations of the hydropower potential at the Inland Ice margin in the years 1974–1980 by the Arctic Consultant Group (ACG) and Vattenbyggnadsbyrån (Colbeck 1974; Kryolitselskabet Øresund 1980).

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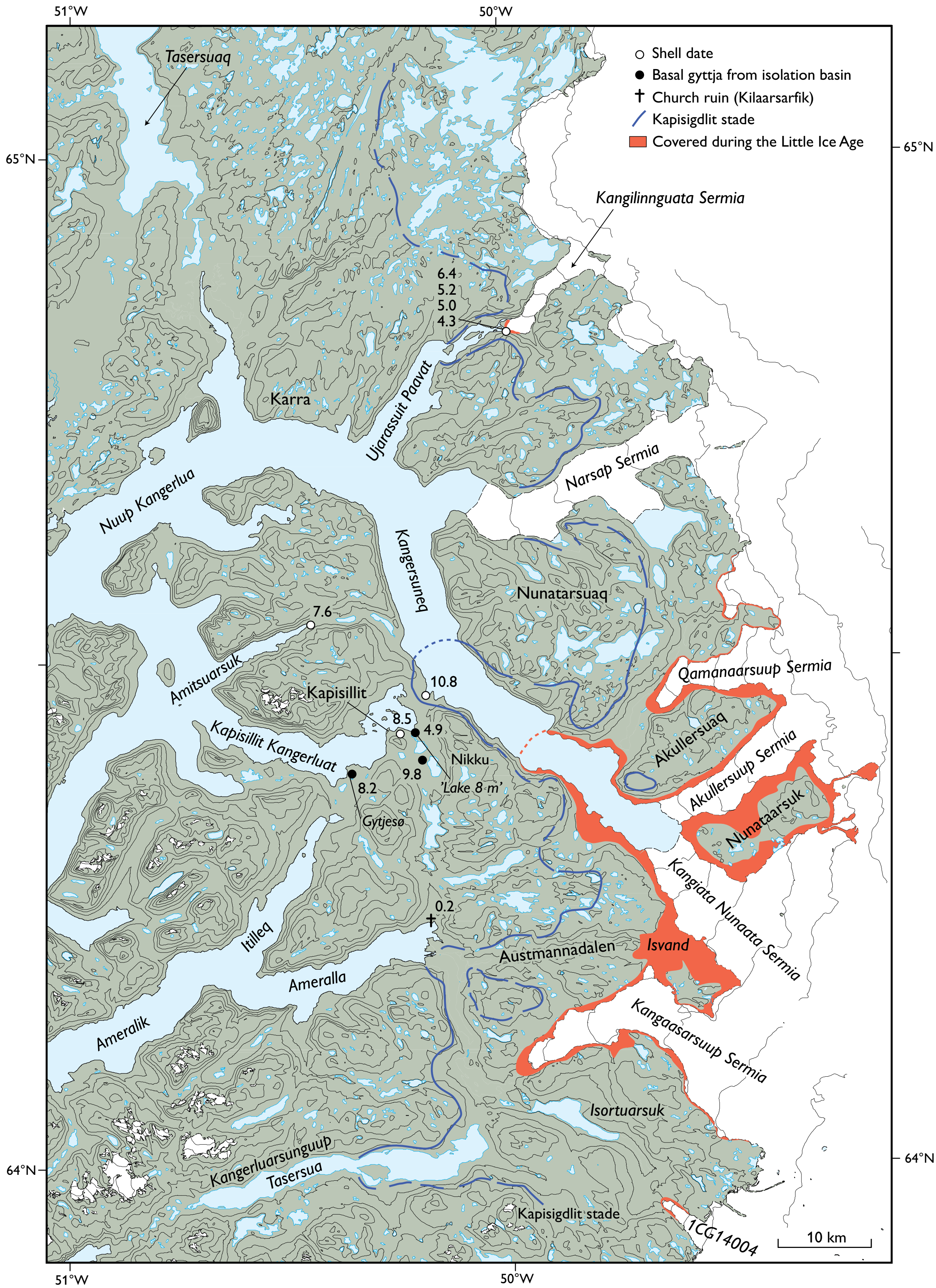
Fig. 3. Map of the inner Nuup Kangerlua and Kangersuneq fjord region, showing the locations of named features and Norse ruins mentioned in the text. The map is based on aerial photographs from 1985; outlined area shown in Fig. 16.

Notes on the Holocene history of the area

The Holocene history of the area is not known in detail. A Quaternary map of the region on a scale of 1:500 000 was published by the Geological Survey of Greenland (Beschel *et al.* 1978), but without explanatory notes or a map description. Notes on the Quaternary history have been published by Weidick (1975a, b) and Long *et al.* (2006).

During the last glacial maximum, *c.* 21 cal. ka BP (cal. ka BP = calibrated to calendar ka before present, where present = AD 1950), the margin of the Inland Ice extended to the edge of the continental shelf according to Vinther *et al.* (2009). The outer coast of the region became ice free during the early Holocene (Bennike & Björck 2002). During the following millennia, net recession continued, but ice-margin deposits mark some halts or minor readvances of the ice margin. The correlation of these ice-margin deposits in western Greenland is uncertain (Weidick 1968, 1984a, b; Kelly 1980, 1985; Long *et al.* 2006). The recession of the ice margin over the present ice-free land followed after the abrupt warming at the Younger Dryas – Holocene transition, which is dated to 11.7 ka before AD 2000 (Rasmussen *et al.* 2006), and which was followed by increasing temperatures during the earliest Holocene.

A characteristic feature of the Kangersuneq area is the wide belt of ice-margin deposits, which can be followed at the heads of Nuup Kangerlua and Ameralik fjords at a distance of 10–30 km outside the present margin of the ice sheet. The deposits indicate a halt or readvance. These Holocene ice-margin features have been variously termed the Fjord stage by Weidick (1968), the Younger Fjord moraine system by Ten Brink & Weidick (1974) and the Kapisigdlit moraine system by Kelly (1985). The term 'the Kapisigdlit stade' is used here to stress the local character of these ice-margin deposits. Near the settlement of Kapisillit, the marine limit drops abruptly from



51°W
50°W
65°N
64°N
Shell date
Basal gyttja from isolation basin
Church ruin (Kilaarsarfik)
Kapisigdlit stade
Covered during the Little Ice Age
Tasersuaq
Kangilinnguata Sermia
6.4
5.2
5.0
4.3
Karra
Ujarassuit Paavat
Narsap Sermia
Nuup Kangerlua
Kangersuneq
Nunatarsuaq
7.6
Amitsuarsuk
Kapisillit
10.8
Qamanaarsuup Sermia
8.5
4.9
Nikku
9.8
'Lake 8 m'
Kapisillit Kangerluat
8.2
Gytjesø
Akullersuaq
Akullersuup Sermia
Nunataarsuk
Kangiata Nunaata Sermia
0.2
Itilleq
Austmannadalen
Isvand
Ameralla
Ameralik
Kangaasarsuup Sermia
Isortuarsuk
Kangerluarsunguup
Tasersua
Kapisigdlit stade
1CG14004
10 km

Table 1. Selected radiocarbon age determinations from the Kangersuneq region

Locality	Lat. (north)	Long. (west)	Elevation m	Laboratory no.	Age 14C yrs BP *	Calibrated age ±1 stdv., BP †	Material	Reference
Johs. Iversen Sø	64°24′	50°12′	100	K-2294	8640 ± 130	9432–10153	Gyttja	Fredskild 1983
Gytjesø	64°23.5′	50°21.5′	57.3	K-2295	7430 ± 100	8031–8402	Gyttja	Fredskild 1983
Kapisillit	64°26′	50°10′	40	K-1036	7560 ± 150	8106–8861	Shells	Weidick 1968, 1972
Amitsuarsuk	64°32′	50°28′	16	I-8596	6670 ± 110	7365–7776	Shells	Weidick 1976
Kapisillit	64°28′	50°11′	5	Ua-3476	9490 ± 105	10570–11109	*Macoma calcarea*	This study
Lake 8 m	64°26′	50°12′	8	K-802	4340 ± 120	4583–5305	Gyttja	Fredskild 1973
Kilaarsarfik	64°15′	50°13′	–2	Archaeol.		*c.* 800		Roussell 1936, 1941

* Ages were not normalised for isotopic fractionation, except for Ua-3476 that was normalised to a $\delta^{13}C$ value of 0‰ on the PDB scale.
† Calibrated according to the CALIB09 dataset (gyttja) and the MARINE09 dataset (marine shells); stdv: standard deviation.

over 100 m a.s.l. west of the moraine system to less than 80 m a.s.l. east of the moraines. On the basis of the radiocarbon ages from the area (Fig. 4) and archaeological information on increasing relative sea level at the church ruin at Kilaarsarfik ('Sandnes') after medieval times (Fig. 3; ruin group no. 51; Roussell 1936), an uplift curve has been proposed (Fig. 5). In the Disko Bugt region, the correlative of this *c.* 9–8 ka old stade was called the 'Fjord stage' by Weidick & Bennike (2007, p. 37).

According to the uplift curve, the Kapisigdlit stade can be dated to 8.1–8.3 ka BP, and it may reflect a readvance as a result of the 8.2 ka BP cold event (Alley *et al.* 1997). The age of the Kapisigdlit stade may correspond to the age of the Tasiussaq moraine system in Disko Bugt (Weidick & Bennike 2007, Young *et al.* 2011). However, a shell of the marine bivalve *Macoma calcarea*, found at Kangersuneq near the settlement of Kapisillit (Figs 4, 6) was dated to 9490 ± 105 ^{14}C years BP (Ua-3476; Fig. 6B), or 10.6–11.1 cal. ka BP (Table 1). The shell was found in a 5–10 m high coastal cliff section with a surface that gradually rises to 13 m a.s.l. at the foot of the proximal side of a Kapisigdlit stade moraine, in a silty boulder diamicton containing concretions with shells (Fig. 6B). The shell fauna included rare but well-preserved shells of *Mya truncata* and *Balanus* sp. The shells probably come from invertebrates that lived at the bottom of Kangersuneq icefjord at a time when the ice margin was located near its present position or farther to the south and east than today. During the Kapisigdlit stade, the shells were dredged from the fjord bottom by the advancing glacier, and deposited in a diamict accumulation, which is now exposed in a coastal cliff section.

Moraines related to the Kapisigdlit stade were first described from Nansens Teltplads (Nansenip Tupeqafia) at the entrance to Austmannadalen from Ameralla (near Norse ruin group 52c; Figs 3, 7). They were called

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Fig. 4. Map of the inner Nuup Kangerlua and Kangersuneq fjord region, showing locations of radiocarbon-dated samples (ages in calibrated ka BP, Tables 1, 2), the approximate position of the Kapisigdlit stade (Weidick 1975a) and the maximum extent of the ice margin during the Little Ice Age (LIA max). The red areas around the present ice margins show the extent of the trimline zone. This zone is broadest around the Kangiata Nunaata Sermia glacier system. The map is based on aerial photographs from 1985.

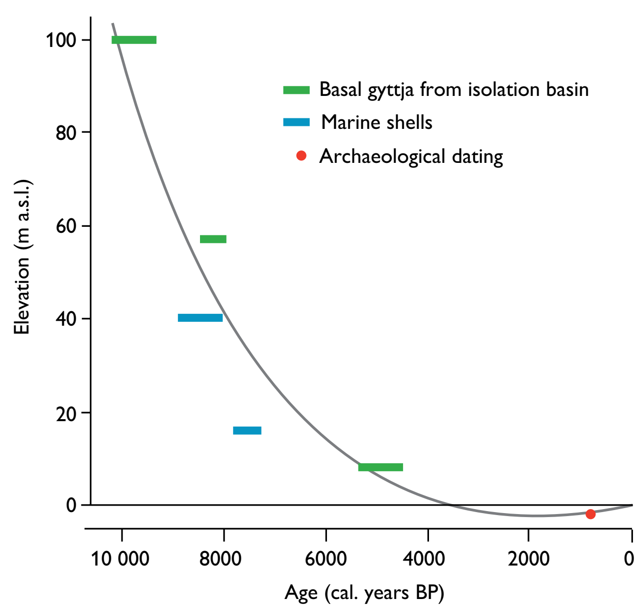


Fig. 5. Model of Holocene relative sea-level changes in the Kangersuneq icefjord area, based on data presented in Table 1; a.s.l.: above sea level.

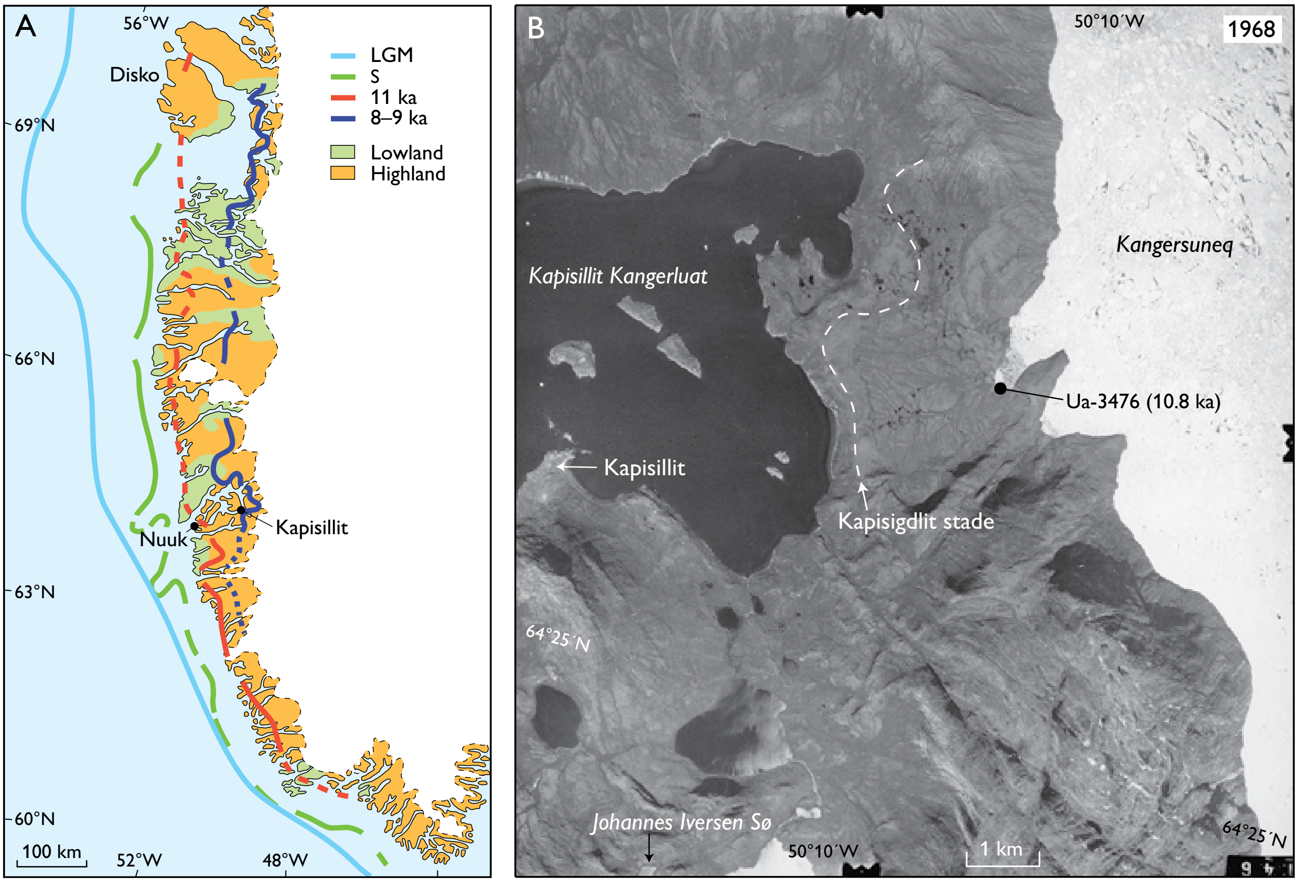


Fig. 6. **A**: Ice-margin positions during the recession of the of the Inland Ice margin in western Greenland (simplified). The numbers indicate approximate mean ages in ka BP. **LGM**: Last Glacial Maximum, dated to *c.* 22 ka BP, the position is according to Vinther *et al.* (2009). **S**: the Sisimiut glacial event. The latter stade was dated to 11–14 radiocarbon ka BP, corresponding to *c.* 12.9–17 cal. ka BP according to Kelly (1985). However, it is possible that the Sisimiut glacial event may correlate with the Younger Dryas cooling (11.7–12.9 cal. ka BP; Rasmussen *et al.* 2006). The stade marked **8–9 ka** shows the approximate position of the 'Fjord stade', including the local Kapisigdlit stade in the Kangersuneq – Nuup Kangerlua area and the Marrait and Tasiussaq moraine systems in Disko Bugt. Lowlands are areas below 300 m a.s.l. **B**: Aerial photograph showing the area around the isthmus at Kapisillit between the fjords Kangersuneq and Kapisillit Kangerluat. Ice-margin features belonging to the Kapisigdlit stade, the location of the shell sample dated to 10.6–11.1 cal. ka BP (Ua-3476) and Johannes Iversen Sø, investigated by Iversen (1953) and Fredskild (1973, 1983) are shown. Aerial photograph from 13 August 1968, Geodetic Institute, route 281R, no. 146.

'jøkelgjærde' (moraine ridge) by Nansen (1890, map) and Bruun (1917, p. 102). This moraine may be cut by a marine terrace at *c.* 50 m a.s.l. Another early observation of ice-margin deposits come from Kangersuneq fjord, near ruin group 15 (Umiivik), where Roussell mentioned that about 700 m up from the ruin site is a large moraine bank running across the valley (Figs 3, 7; Roussell 1941, pp. 60–61).

The recession presumably continued after the Kapisigdlit stade, up to the peak of the Holocene thermal maximum at *c.* 7–6.5 ka. At around this time the ice margin was generally located inland of the present position. It is not known how far east the ice margin retreated. However, a minimum estimate can be given for the time interval during which the ice margin was behind the present margin, based on ages of marine shells in concretions sampled from Little Ice Age moraines and from the alluvial plains in front of the outlet of Kangilinnguata Sermia, and dredged by the glacier from the bottom of the fjord. Age determinations of four samples gave ages of 6.4 to 4.2 cal. ka BP (Table 2). It is presumed that the net readvance was characterised by separate readvances of increasing magnitude, which generally culminated towards the end of the Little Ice Age at AD 1700–1900. The geomorphology of moraine localities and the content of fossils in the deposits were described by the German geologist K. Gripp (1932, 1975), who also described marine fossils from Alanngorlia at Sermeq glacier and Frederikshåb Isblink.

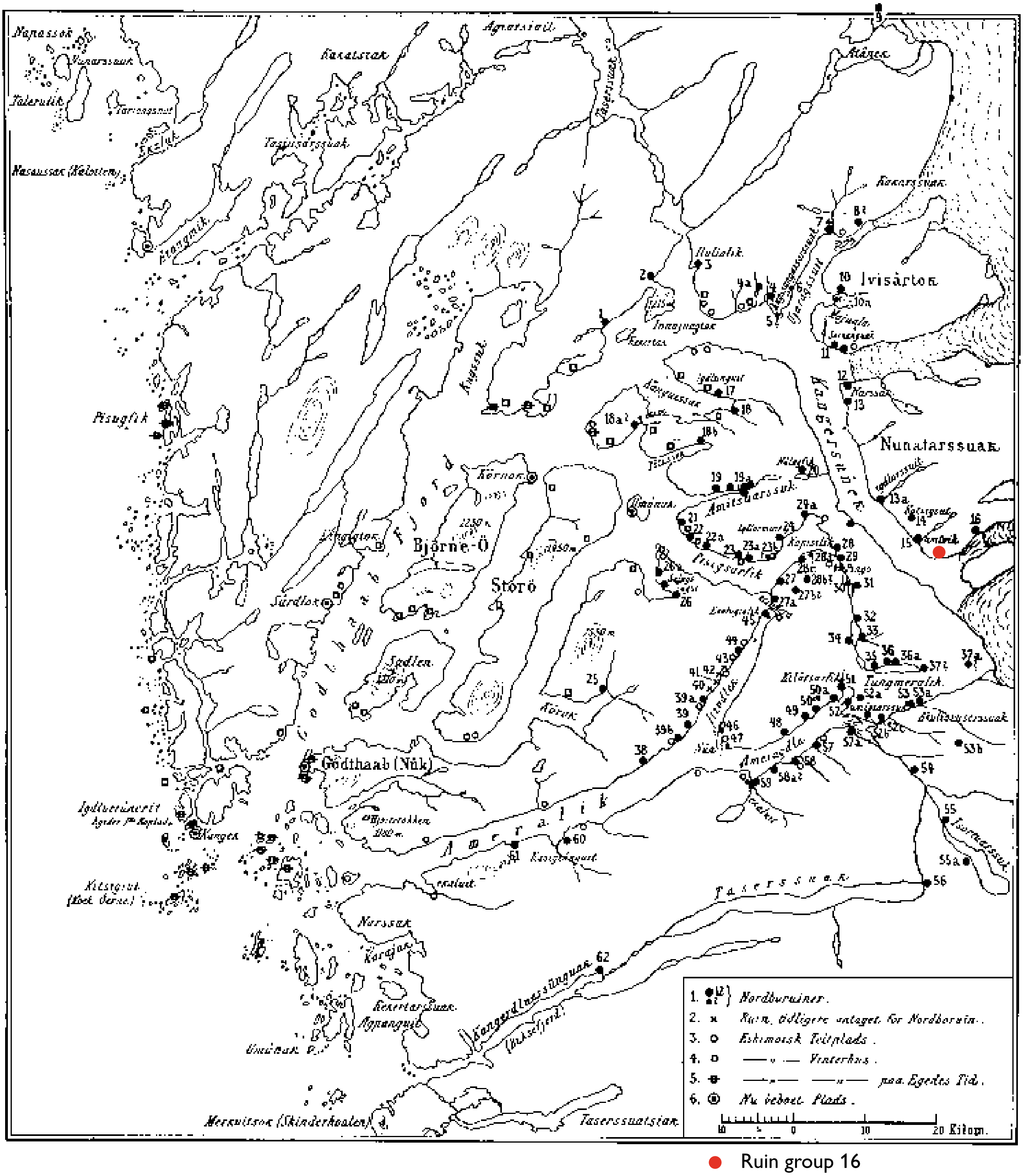


Fig. 7. Norse and Eskimo ruin groups in the area between Nuup Kangerlua (Godthåbsfjord) and Ameralik fjord (Bruun 1917); Bruun's numbers for ruin groups are still being used today. D. Bruun used a map by J.A.D. Jensen (drawn after field work in 1884 and 1885) as a basis for plotting archaeological sites after collecting information in Greenland in 1903 and using additional information from O. Bendixen after his travels in 1916. The map shows that the Norse farms and churches are found in the interior part of the ice-free land. Jensen's map was in general use up to the 1930s. Legend: **1**. Norse ruins. **2**. Ruins previously believed to be Norse. **3**. Eskimo tent sites. **4**. Eskimo winter houses. **5**. Eskimo winter houses from the time of Hans Egede (younger than 1721). **6**. Inhabited sites (i.e. from 1884 to the 1930s). The red dot marks the location of ruin group 16 according to Roussell (1941).

Table 2. Neoglacial radiocarbon ages of shells from the bottom of Ujarassuit Paavat (64°50´N, 50°0´W)

Laboratory no.	Age ^{14}C yrs BP *	Calibrated age ±1 stdv., BP †	Reference
Ua-3473	5590 ± 90	6240–6628	This study
Ua-1089	4535 ± 110	4951–5544	Weidick 1993
Ua-3475	4280 ± 95	4683–5244	This study
Ua-3474	3780 ± 70	4057–4448	This study

* The radiocarbon ages were normalised for isotopic fractionation to a δ^{13}C value of –0‰ on the PDB scale.

† Calibrated according to the MARINE09 dataset; stdv: standard deviation.

Moraine systems (partly with ice-cored moraines) are especially well developed around the Kangiata Nunaata Sermia glacier system. Relicts of shear moraines can be seen in Kangersuneq *c.* 11–12 km behind the Little Ice Age maximum extent as defined by the extension of the trimline zone. In the following, this advance is called the '1920 stade'.

The first overview of the bathymetry of the Nuup Kangerlua region was compiled by Beschel *et al.* (1978), although data were lacking from major parts of the interior fjords. Mortensen *et al.* (2011) presented a depth profile of Nuup Kangerlua and Kangersuneq. The depth of the inner part of Nuup Kangerlua is about 600 m, whereas the depth in Kangersuneq icefjord is around 300–400 m (Fig. 8). A major threshold is found at the Little Ice Age maximum, where the depth is *c.* 150 m. Another smaller threshold is found *c.* 8 km inside this, with a depth of *c.* 300 m. The latter is found 1–2 km in front of the 1920 stade. A third threshold may occur at the 2010 frontal position of Kangiata Nunaata Sermia, where the water depth is 210–240 m. The thresholds are separated by depressions with depths of 350 and 400 m (Fig. 8). The depressions may have been eroded during time periods when Qamanaarsuup Sermia (during the Kapisigdlit stade) and Akullersuup Sermia (during the Little Ice Age maximum) were tributaries to the Kangiata Nunaata Sermia glacier system. The present frontal height of Kangiata Nunaata Sermia is <50 m; the glacier front is probably mainly resting on the fjord bottom.

Geological, archaeological and historical information on glacier fluctuations and sea-level changes

The uplift curve (Fig. 5) shows a rapid emergence of land in the early Holocene, which was a consequence of the decrease of the ice load over the region. Uplift was followed by submergence in the late Holocene. Indications of relative submergence were already noted by Arctander (1793) and Pingel (1841, 1845) based on observations of archaeological sites situated at or below the present sea level. Their observations were confirmed by Matthiassen (in: Gabel-Jørgensen & Egedal 1940, pp. 8–10), Roussell (1936, 1941) and Larsen & Meldgaard (1958) based on

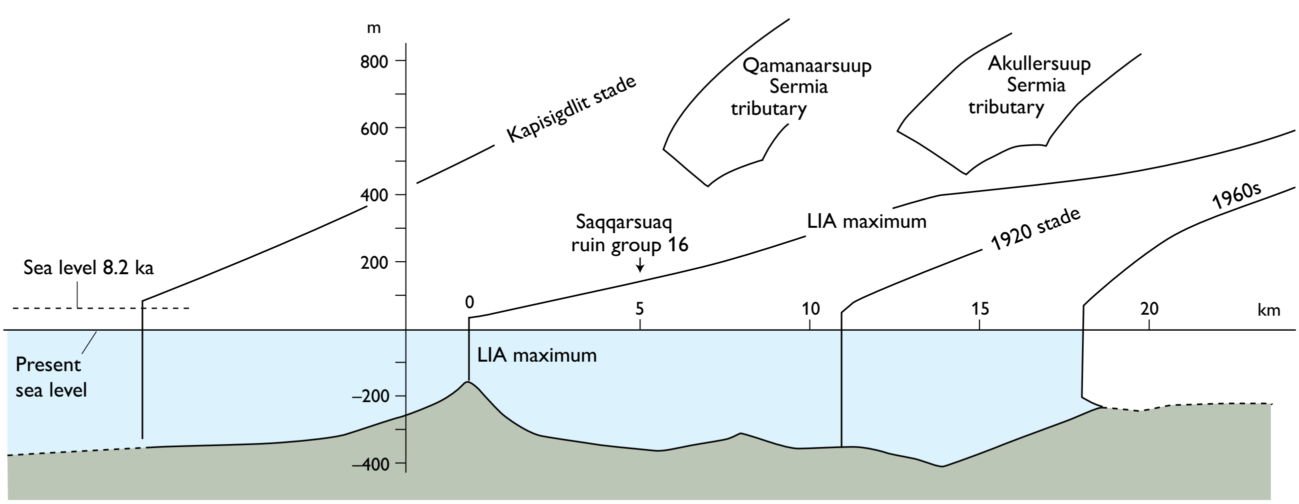


Fig. 8. Depth profile of Kangersuneq icefjord showing profiles of Kangiata Nunaata Sermia during the Kapisigdlit stade (8.2 cal. ka BP?), during the Little Ice Age (**LIA**) maximum (1700s), during the 1920 stade (*c.* 1920) and during the 1960s. The minor depression of the fjord bottom 4–6 km off Qamanaarsuup Sermia and *c.* 14 km off Akullersuup Sermia may be due to the erosive effect of the frontal part of Kangiata Nunaata Sermia glacier system when the two tributary outlets joined the main glacier Kangiata Nunaata Sermia.

archaeological investigations, as well as by Saxov (1958, 1961) based on geophysical work. A review of these investigations was published by Weidick (1996).

Investigations have been carried out at a few localities in southern West Greenland by dating the timing of isolation of lakes from the sea using pollen analysis and radiocarbon age determination. The pioneers of such investigations in the area were Iversen (1953) and Fredskild (1973, 1983). More recent investigations have been made by Long *et al.* (2009) at a locality on the outer coast south of Sisimiut, and by Bennike *et al.* (2011) at a locality near Sisimiut. The relative sea-level history in the inner part of the Nuuk region was undoubtedly different from that of the Sisimiut region 300 km to the north-west, but the fact that the church ruin at Kilaarsarfik ('Sandnes') is now covered by the sea at high tide shows that this region has been transgressed.

Dietrich *et al.* (2005) suggested a recent uplift of about 1 mm per year near Sisimiut and a subsidence of 2.2 mm per year at Kapisillit in the inner region of Nuup Kangerlua based on GPS measurements at a number of stations in western Greenland. Long *et al.* (2009) suggested that the difference reported by Dietrich *et al.* (2005) could be a consequence of the behaviour of the ice margin in the two areas. More recently, Bevis *et al.* (2012) reported an uplift rate of 7.5 mm per year at Kapisillit. Although this figure may be uncertain due to problems with uplift processing, it is likely that the uplift rate has accelerated.

Roussell (1936, p. 8–10; 1941, p. 14–18) in his treatise on the Norse farms and churches in the inner parts of Nuup Kangerlua and Ameralik made two important observations on the environmental situation of the Norse settlements:

1. The relative sea level was some metres lower at the Kilaarsarfik church (ruin group 51, Figs 3, 7) at the head of Ameralik fjord in early medieval time than today. We suggest that the following relative sinking of the land is primarily related to the increasing glacier load during the Neoglacial.

2. The many farms along the head of Ameralik, in Austmannadalen west of Kangiata Nunaata Sermia, at the head of Ujarassuit Paavat north of Kangersuneq and in Kangersuneq icefjord must have been more accessible from the sea in medieval times than at present, where kilometre-long tidal flats or calf-ice accumulations are found at the heads of the fjords. The tidal flats reflect a large increase in sediment supply, probably due to a marked glacier advance after the Norse disappeared from the area, presumably around 1345 when the Norwegian priest Ivar Bardarsson visited the area (Gad 1967; Arneborg 2004).

As mentioned in the introduction, data on glaciers and glacier changes are sparse up to the first half of the 1800s. However, in the mid-1800s there was a growing international interest in the Arctic regions. The first systematic investigations of western Greenland were undertaken between the 1870s and 1900 by the Commission for the Direction of the Geological and Geographical Investigations in Greenland. In addition to geological and geographical studies, archaeological, botanical and other scientific investigations were carried out. The results were published in *Meddelelser om Grønland*, which was issued by the commission.

Data from aerial photographs and satellite images

The use of aerial photography in Greenland began in the 1930s, in connection with a new systematic mapping programme (Wenzel-Petersen 1970; Nielsen 2000). The oldest photographs were oblique ones. During the Second World War, the US Air Force covered parts of Greenland with a combination of oblique and vertical photographs (trimetrogon). Oblique aerial photographs were also used by the Geodetic Institute in following years. These photographs cover large areas, but distant objects show little detail and more recent series are thus all vertical.

Aerial photographs from Greenland have been acquired and collected since the 1930s by the former Geodetic Institute which was established in 1928 and was originally an institution under the War Ministry (Krigsministeriet; Helk 1954; Wenzel-Petersen 1970, p. 31). The Geodetic Institute produced and sold maps and copies of aerial photographs. The total collection of aerial photographs was available without restrictions, even during the cold war. On 1 January 1989, the Geodetic Institute became part of the National Survey and Cadastre (Kort & Matrikelstyrelsen), currently in the Ministry of the Environment (Nielsen 2000, p. 77).

In addition to topographical mapping, the West Greenland photographs from the 1930s were also used in connection with archaeological investigations of the Norse ruins. The many details seen on the photographs made them suitable for archaeological and other scientific investigations. However, the old series did not cover all the ice-free land, and it was not until 1985 that a total coverage of vertical aerial photographs was achieved.

Since the 1970s, satellite images have been used to map glacier changes. These images cover large regions and are available at short intervals. Data from satellites can be used in mass-balance calculations of specific sectors (Dahl-Jensen *et al.* 2009). However, in this work we have only used data from satellites to update information from historical sources and aerial photographs.

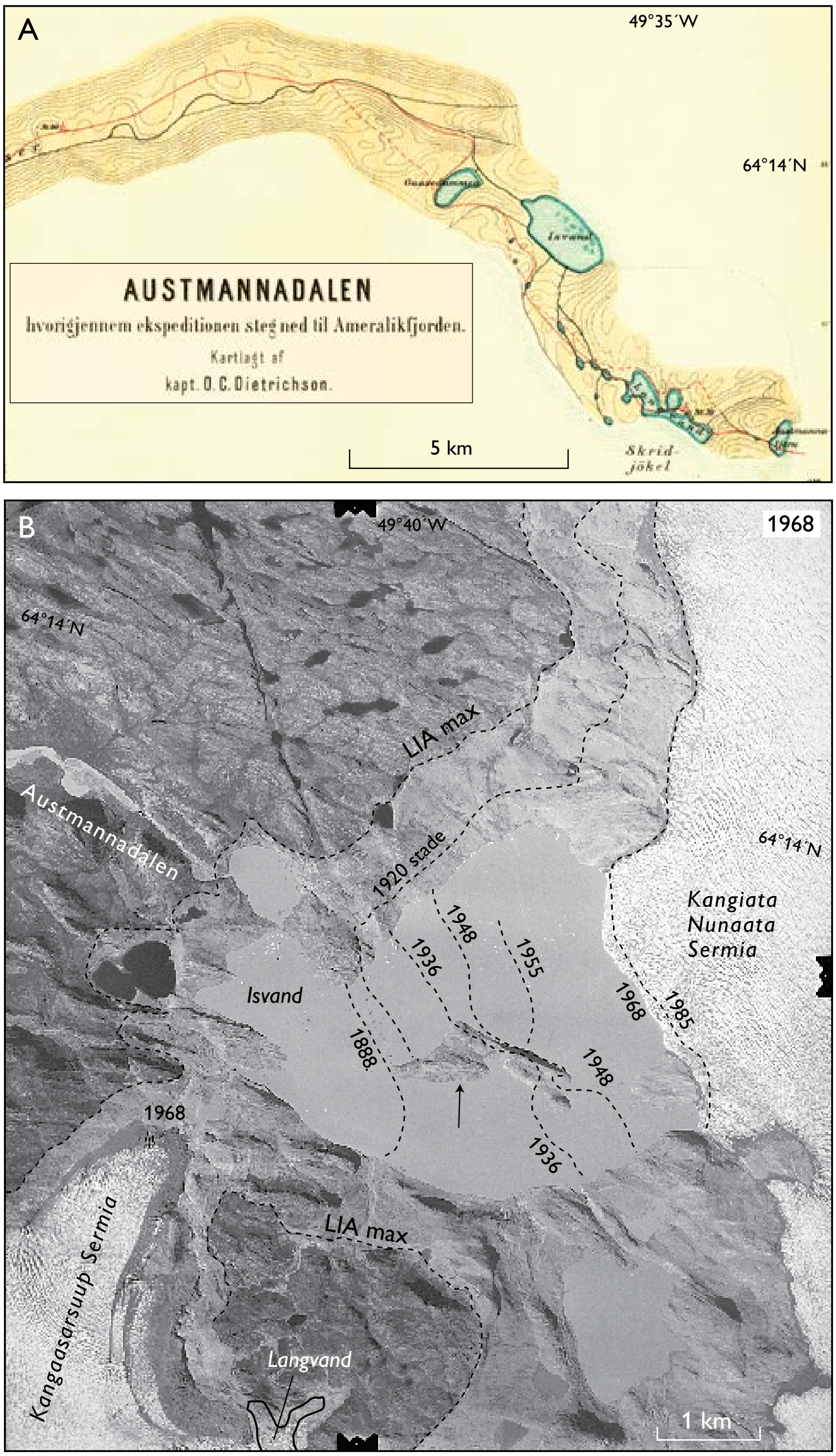


Fig. 9. **A**: Isvand and the eastern part of Austmannadalen in 1888. Eastern part of a map by O.C. Dietrichson (Nansen 1890). Skridjökel: glacier, here part of a southern outlet of the Inland Ice (Kangaasarsuup Sermia). Isvand is drawn fairly schematically, but at its east side one can see the damming glacier marked by icebergs in the lake. **B**: Isvand and its discharge into the river through Austmannadalen. Vertical aerial photograph from 16 August 1968, Geodetic Institute, route 281T, no. 85. The arrow indicates the island discussed in the text. The recession of the damming ice margin is given by approximate positions of the ice margins with years of observations from 1888 to 1985. The recession was probably interrupted by minor advances, with the most pronounced culminating just before 1920 (marked 1920 stade). The most impressive change occurs in the area between the present glacier margin and the limit of the maximum ice coverage during the Little Ice Age. This limit is marked **LIA max**, and the area behind is still relatively barren even though major parts of this trimline zone have been free of ice for around 200 years. The position of the front of Kangiata Nunaata Sermia was stable between 1985 and 2010. After Weidick & Citterio (2011).

Glacier changes in the Kangersuneq area

The description and evaluation of glacier changes primarily concern the fronts of the glaciers Kangiata Nunaata Sermia, Akullersuup Sermia, Qamanaarsuup Sermia and Kangilinnguata Sermia although the record from Kangiata Nunaata Sermia is supplemented by data from the locality of Isvand, a former ice-dammed lake situated on the western flank of the glacier (Figs 3, 9). The individual glaciers or localities are treated separately, the presentation of the historical and modern data being followed by an evaluation of these datasets in terms of the glacial history.

The former ice-dammed lake Isvand

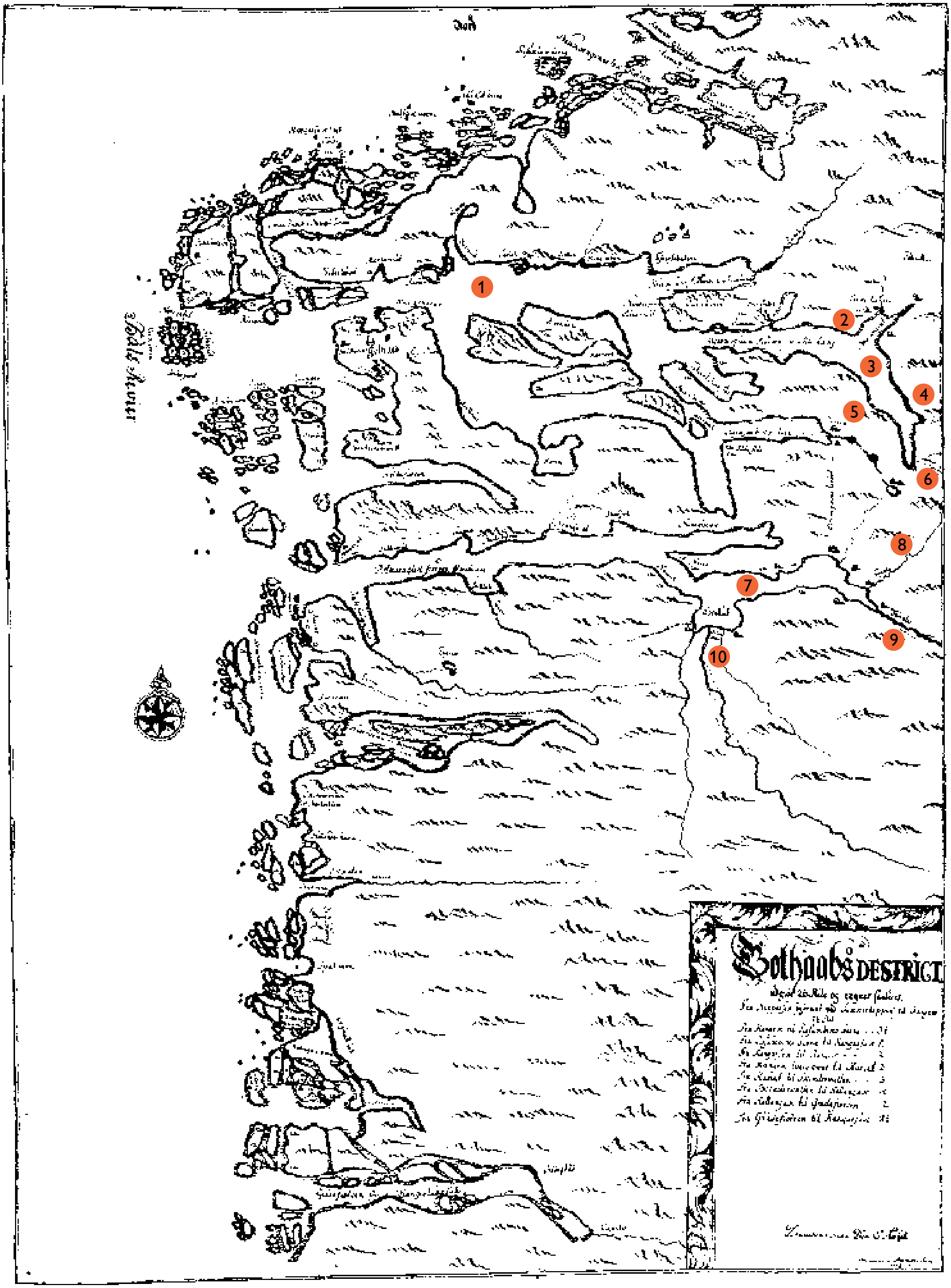
The description below concentrates on the area east of Austmannadalen, in particular the area including the former ice-dammed lakes Isvand and Langvand, located south-west of Kangiata Nunaata Sermia and north of Kangaasarsuup Sermia (Figs 3, 9). The earliest information about the ice margin in this area was given by Hans Egede (1925, p. 104) in 1723. He refers to observations by reindeer hunters, who from Ameralik fjord presumably travelled up Austmannadalen, and observed the large 'ice mountain' which expanded over the mountains and undoubtedly was connected with the ice cover and mountains that Egede had seen farther south. The hunters saw a large lake under the 'ice mountain', into which large ice lumps had fallen from the 'ice mountain', and Egede compared it with an earlier mentioned 'Ujarachsuach' (now: Kangersuneq), which also was full of icebergs that had fallen from the ice. It is uncertain whether this description refers to Isvand, but Isvand was the largest of the ice-dammed lakes in this area at the head of Austmannadalen. This ice-dammed lake formed after the Little Ice Age maximum extent of the ice, when the whole area of the later Isvand was ice covered. The comparison to the ice conditions in 'Ujarachsuach' fjord is also open to question. It appears that this name was sometimes used for the present Kangersuneq, but usually it was only used for the fjord Ujarassuit Paavat (Figs 3, 10).

It may also have been via Austmannadalen that governor Claus Enevold Paars in April 1729 visited the ice margin, sailing from Nuuk to the head of Ameralik and then walking through Austmannadalen with a party of Danes, guided by two Greenlanders to reach the Inland Ice. From his observations near the ice margin, he described glacier crevasses, the crystalline structure of the glacier ice, and erratic boulders on the ice surface (Bobé 1936a, p. 26, 1936b, pp. 186–189). On the trip he also found ruins, but he does not mention the ice-dammed lakes at all. If large ice-dammed lakes existed, they must have formed an obstacle for approaching the Inland Ice margin and would probably have been recorded.

Egil Thorhallesen, a missionary who lived in Greenland between 1765 and 1775, toured the central parts of western Greenland, especially in 1774 and 1775. He published an account of the Norse ruins (Thorhallesen 1776), but his original description of the country, its people and nature was not published until 1914 by Bobé (Thorhallesen 1914, including maps of the area). Thorhallesen mentioned several Norse ruins, amongst others at a locality called Kangia, presumably at the head of Ameralla: *In the eastern end of the bay several ruins from the old Europeans are also found; some may also be situated on high ground and some may have been covered by the glacier-ice in recent time. This is described in more detail in the "Efterretning om Rudera i Baals Revier [Treatise on rudera in Baals Revier]".* (Thorhallesen 1914, pp. 51–52; authors' translation.)

It is difficult to locate Thorhallesen's place names from his map (Fig. 10). 'Baals Revier' is Nuup Kangerlua (Godthåbsfjord). The river named 'Laxelv' is probably the river running through Austmannadalen. 'Storelv' is probably the Naajat Kuuat river, which drains the glacier Kangaasarsuup Sermia (not shown on Thorhallesen's map, Fig. 10) and also drains the large lake Isortuarsuk.

The head of Ameralik and Ameralla fjords was called 'Kangia' by Thorhallesen, but in a note by Bobé (Thorhallesen 1914, p. 51) it was changed to 'Umiviarsuit', which is a locality close to the Kilaarsarfik church ruin (Bruun's map 1917, Fig. 7). Thorhallesen noted that the length of Ameralla fjord from Eqaluit to its head at Kangia (or Umiviarssuit) is 2 Danish miles (15 km), which is close to the distance on modern maps. On Thorhallesen's map, the lengths of the fjords are generally close to distances on modern maps whereas the orientations of the individual parts are distorted. Roussell (1941) noticed that the route to the Norse ruins behind the present extensive tidal flats may have been easier in the 18th centu-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ry than today. It is possible that much of the sedimentation took place after Thorhallesen's visit. Sedimentation rates may have increased due to the increased ablation that accompanied glacier recession in the 1800s.

The ruins at Tummeralik were also mentioned by the early explorers of the region, and from a visit to the area around Tummeralik on 1 June, 1810 (Giesecke 1910, 254–259). Giesecke described the ruins at Tummeralik as well as the ice margin of the 'Eisblink', which may be the ice margin situated *c.* 5 km east of Tummeralik (Tummerallip Tasersua). Ruin group 37a shown on Bruun's map (Fig. 7) is not mentioned or plotted on newer maps of Norse ruins in the area (Gad 1967; Kort & Matrikelstyrelsen 1993) and may therefore not exist, at least not as Norse ruins. From a camp at 'Auaitsirksarbik' (3–4 km from the ice margin of the glacier?) in 1810, Giesecke (1910, pp. 257–258) described the ice margin: *This evening I went to the incredibly beautiful glacier (Sermersoak in Greenlandic), which is surrounded by a lake. The glacier is up to 80 feet high. Its margin is split into pointed cone-shaped prisms that are separated by deep crevasses, and some of the cones are almost pyramid-shaped. The surface of the glacier has large, often undulating peaks and depressions. The first impression is ghostlike; and the surrounding, completely barren area put me in a melancholy mood; it seemed to me that I was in another world. It was midnight – I was resting alone in this depressing area, which had presumably never before been visited by any European. However, soon I enjoyed an uplifting drama in this desert when the sun rose behind this colossal mirror of ice...* (authors' translation).

Facing page:
Fig. 10. Map of the 'Gothaabs Destrict' compiled by E. Thorhallesen in 1776, accompanying the report on his voyage to central West Greenland (Thorhallesen 1914). The map gives an impression of the geographical knowledge gained by the end of the 1700s of the area of Greenland that was best known at that time. The numbers show the location of some of the place names used in this study: **1**: Nuup Kangerlua (Godthåbsfjord). **2**: Ujarassuit. **3**: Kangersuneq. **4**: Narsap Sermia. **5**: Isthmus between Kapisillit Kangerluat (on the map: 'Pisigsarfik fjorden') and Kangersuneq. **6**: Kangiata Nunaata Sermia. **7**: Ameralla. **8**: Austmannadalen. **9**: Naajat Kuuat. **10**: Eqaluit. The map published in 1914 measures 32 × 23 cm. E. Thorhallesen (1734–1789) was born in Iceland and was a priest in Greenland (1765–1775). He made a description of West Greenland in connection with mapping of Norse ruins.

Further observations by Giesecke may refer to the development of a trimline zone and ice- marginal lakes, but his description is unclear.

Several old maps of the area, drawn by local Greenlandic hunters, are housed in a collection at the Royal Library in Copenhagen. This collection was established on the initiative of Hinrich Rink, the inspector and later director of the Royal Greenland Trade. He encouraged local hunters to collect information and draw maps of their hunting areas. The linguist and missionary, Samuel Kleinschmidt, also participated in this collection of information; his map of the region (Fig. 11) provides the best overview of the area from this time. The map was presumably drawn in the years before 1859, based on various sources and printed in 1860 (Kleinschmidt 1860). On this map, a lake is apparently indicated at the site where Austmannadalen ends at the glacier margin, although it is possible that this lake is just two converging rivers. On newer versions of the map from the last half of the 1800s, this feature was sometimes coloured to indicate a lake.

Kleinschmidt's map was based on maps prepared by local hunters and their information, as well as on his own sketches, bearings and data from surveyors. His map is recognised as being of a high standard for the time. A comparison of Thorhallesen's map from 1776 (Fig. 10) with Kleinschmidt's map from 1860 (Fig. 11) shows major improvements. The importance of Kleinschmidt with regard to the geographic knowledge of the Nuuk region is emphasised by Wilhjelm (2001, pp. 144–152).

J.A.D. Jensen reported from his visit to the area in 1885 (Jensen 1889, p. 88) that he could not enter the interior of Kangersuneq due to dense calf ice in the fjord. Furthermore he noted: *In later years the calf-ice concentration [in Kangersuneq] has increased considerably, and the Greenlanders are now rarely able to travel there, which was quite common earlier.* (Authors' translation.) This could mean that the glacier had receded. However, compared with the earlier maps of the 1800s, J.A.D. Jensen's map from his expedition is more accurate and a later version of this map was used as the base map for Bruun's systematic mapping of the Norse ruins in the area (Bruun 1917). The map of the interior parts of Kangersuneq (Fig. 7) may well have been drawn from the mountain 'Nikok' (Jensen 1889, pp. 88–89). According to Jensen's travel report, this mountain is 3130 feet high (970 m), and he noted that he had a good view of the interior landscape around the southern part of Kangersuneq. It must be the same mountain, named Nivko, which on the map published by Kort & Matrikelstyrelsen (1993) is shown with

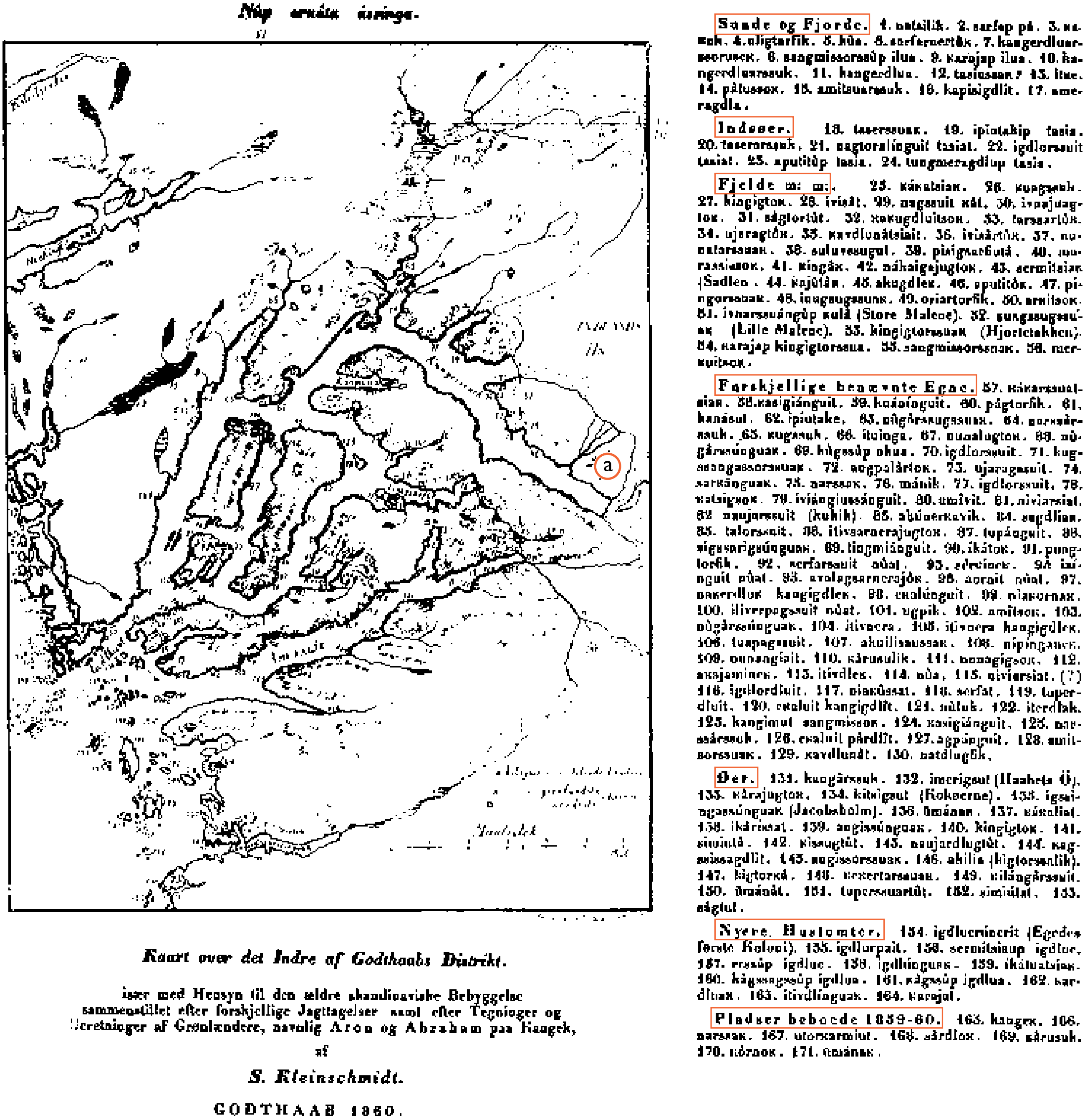

Fig. 11. Map of the Nuuk area (title in Greenlandic). The Danish text below the map translates: *Map of the inner part of Godthåb District, with special regard to the former Scandinavian settlements. Compiled from various observations, as well as from drawings and accounts by Greenlanders, especially Aron and Abraham from Kangeq. By S. Kleinschmidt, Godthaab 1860. Printed in the printing office of the Inspectorate.* (Authors' translation.) The Danish headings to the right of the map translate as follows: **Sunde og Fjorde**: straits and fjords. **Indsøer**: lakes. **Fjelde m:m:**: mountains etc. **Forskjellige benævnte Egne**: various mentioned areas. **Øer**: islands. **Nyere Hustomter**: newer house ruins. **Pladser beboede 1859–60**: Inhabited settlements 1859–1860. The legend translates as follows: **betegner … beboede Pladser**: designates … inhabited settlements. **… grønlandske Ruiner**: Eskimo ruins. **… nordiske Ruiner**: Norse ruins. The scale (**Maalestok**) is in Danish miles (1 Danish mile = 7.5 km); **a:** Akullersuaq. The map is reproduced from Gulløv (1983). A printed version of the original map is in the Royal Library in Copenhagen; the map in this version measures 26 × 19 cm. S. Kleinschmidt (1814–1886) was a teacher at the Teacher's College in Nuuk (Godthåb Seminarium); he published a famous Greenland grammar and added many details to the geographical knowledge of West Greenland.

an altitude of 924 m a.s.l., and which is located on the south-western side of Kangersuneq near the settlement Kapisillit. Jensen also described ice-dammed lakes along the south side of Narsap Sermia on the semi-nunatak Nunatarsuaq and their draining through Narsap Sermia and he mentioned the innermost semi-nunatak Nunataarsuk. In view of the details provided, the approximate position of the front of Kangiata Nunaata Sermia south of the semi-nunatak Akullersuaq may be realistic (Figs 3, 4), but the front may also have been copied from Kleinschmidt's or other early maps from the middle of the 1800s.

The following information about the area between Kangiata Nunaata Sermia and Ameralik fjord in 1888 is taken from F. Nansen's description (Nansen 1890). Nansen crossed the Inland Ice from South-East Greenland to Ameralik fjord in West Greenland. He described the descent from the Inland Ice and compiled a map over parts of the ice margin, the ice-dammed lakes Isvand and Langvand and the valley (Austmannadalen) leading down to Ameralla fjord (Fig. 9). All three names were given by Nansen's expedition. The area was mapped by O.C. Dietrichson; only the western part of it concerning Isvand is shown here (Fig. 9A). This map from 1888 shows that the marginal lakes are situated inside the trimline zone, which must have formed before this year. If Kleinschmidt's map from 1860 shows a lake at this site, Isvand must have existed around or before the middle of the 1800s. Initial thinning of the glacier implies that recession from the maximum extent of Kangiata Nunaata Sermia began before the visit by Nansen's expedition. The following recession can be seen on aerial photographs from 1936 to 1985 (Fig. 9B).

The Norse ruins in Austmannadalen were located in 1934 and excavated in 1937 (Roussell 1941, p. 14). In connection with these activities, the area was covered by aerial photographs in 1936. The photograph in Fig. 9B from 1968 shows the eastern part of Austmannadalen with the ice-dammed lakes Isvand and Langvand. The glacial extent in 1936 can be compared with the situation in 1888 (Nansen 1890, map; Fig. 9A), as well as with an aerial photograph from 1985 and an ASTER image from 2010 (Fig. 12).

The photograph from 1968 shows the Inland Ice margin surrounded by a wide trimline zone. It is difficult to differentiate between the ice-dammed lakes Isvand and Langvand (Fig. 9B) and the surrounding trimline zone as the lakes were filled with the same silt that covers the vegetation-poor trimline zone; this is in marked contrast to other lakes in the area that appear black on the photographs. The extent of the trimline zones indicates that the maximum coverage of the margin of the Inland Ice occurred before 1888, but also that the ice margin at this locality in 1888 had already receded 2–3 km from the Little Ice Age maximum. On the aerial photographs from 1936 and subsequent years, a series of ice-margin features, which must have formed during an advance before the 1930s, can also be seen. They can be followed down to the former semi-stable front of the Kangiata Nunaata Sermia glacier system situated *c.* 12 km behind the Little Ice Age maximum. The stade marked by these moraines is the 1920 stade mentioned earlier.

On the aerial photographs from 1936, an ice-free headland, peeping out from the ice margin in the lake, is seen. Following recession until 1985 (Fig. 9B), this headland became an island (see arrow on Fig. 9B) and the recession of the ice margin during this period must be *c.* 2 km. The shape of the Isvand lake in the period 1936–85 remained unchanged, indicating a nearly permanent lake level at *c.* 360 m a.s.l. (Kort & Matrikelstyrelsen 1993), with no periodic sudden drainage of Isvand under or through Kangiata Nunaata Sermia to Kangersuneq and with a permanent discharge through Austmannadalen.

Comparison of the 1985 photograph with a Landsat image from 2009 shows a dramatic change in the area. Satellite images from between 1987 and 2010 indicate that the shrunken Isvand lake underwent sudden drainage events via Kangiata Nunaata Sermia in 2004 and 2009. It appears that the continuous thinning of Kangiata Nunaata Sermia resulted in drainage of Isvand. The fluvial discharge through Austmannadalen to Ameralla and Ameralik fjords must now be just as modest as it was during the Norse period. However, the area formerly covered by Isvand is now covered by a layer of silt and the head of Ameralla is filled up with extensive tidal-flat silt accumulations; these features testify to the former influence of Isvand and its drainage through Austmannadalen.

Photographs taken by Dirk van As on 26 August 2010 apparently show a renewed filling up of the ponds of the former Isvand. This is also seen on ASTER images from earlier in 2010 (Fig. 12). Presumably the lake remnants are now partly emptied by periodic drainage via Kangiata Nunaata Sermia.

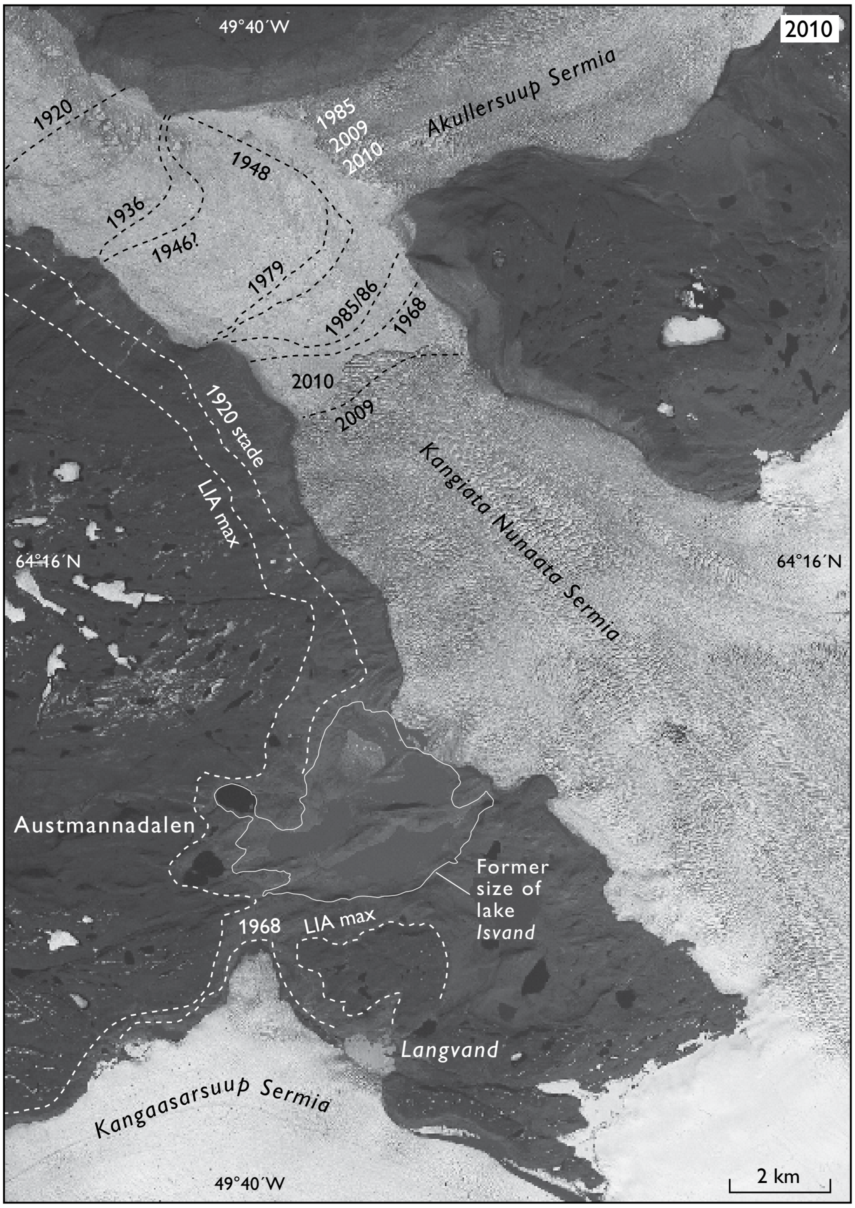

Fig. 12. Advanced spaceborne thermal emission reflection radiometer (ASTER) satellite image of the area in front of Kangiata Nunaata Sermia and former size of lake Isvand showing the situation in 2010. The outline of the former lake Isvand in 1968 is shown with white lines (see Fig. 9B). The approximate positions of the front of Kangiata Nunaata Sermia are shown for the period c. 1920–2010; the Akullersuup Sermia ice front remained nearly stationary between 1985 and 2010. **LIA max**: Little Ice Age maximum. After Weidick & Citterio (2011).

Evaluation

During the time of the Norse settlers, the river running through Austmannadalen only received water from the restricted hydrological basin of Austmannadalen and therefore had a very modest discharge. The following culmination of the Little Ice Age is uncertain, but the ice margin was probably situated at the pass point between Austmannadalen and the valley around Isvand. H. Egede visited the region in 1723 and mentioned an expanding 'ice mountain' and water 'under' (and around?) the ice (Egede 1925, p. 104). In 1729, C.E. Paars traversed the area, but he does not mention an ice-dammed lake (Bobé 1936b, pp. 186–187). It is therefore possible that Isvand did not exist and the ice margin may have been located at the pass point between Isvand and Austmannadalen (at *c.* 360 m a.s.l.).

During the period when Isvand existed in the 1700s, 1800s and the 1900s, the pass between Isvand and Austmannadalen received meltwater from large parts of the western ablation areas of Kangiata Nunaata Sermia that drained via Austmannadalen to Ameralla. The lake may have had the same level at *c.* 360 m a.s.l. throughout the period of its existence, and the development of the lake reflects the recession of the ice margin, which led to a growth of the lake area, but without any essential change of its outline. After the rapid drainage of the lake through Kangiata Nunaata Sermia in 2004 and 2009, the ice margin became more stable, and the fluvial regime in Austmannadalen became similar to that in medieval times. The only change compared with the medieval conditions is the blanket of silt and mud that now covers the trimline zone including the earlier lake floor of Isvand. In addition, an extensive tidal flat has formed at the head of Ameralla fjord.

The glacial events in the Austmannadalen and Isvand area can be summarised as follows:

***c.* 1700 – *c.* 1750:** The advance leading to the Little Ice Age maximum presumably occurred *c.* 1729 and led to the formation of Isvand, the ice-dammed lake, in perhaps 1723. This implies that significant drainage of meltwater through Austmannadalen from Kangiata Nunaata Sermia took place. Subsequent minor recessions and readvances of the ice margin may have occurred during this period.

***c.* 1750 – *c.* 1800**: Initial thinning of the western flank of Kangiata Nunaata Sermia. The size of Isvand depended on the minor fluctuations of the glacier. Over this time period, the area drained via Austmannadalen to Ameralla. The size of Isvand was restricted.

***c.* 1800–1888:** The ice margin at Isvand receded *c.* 2.5 km, presumably with large variations. The rate of recession was reduced towards the end of the period.

1888 – *c.* 1920: The decreasing recession rate during this period shifted to a marked advance of the glacier margin at some time well before 1920, and ended with the culmination of the advance *c.* 1920. This may have been due to low average annual temperatures in West Greenland. Hence at Nuuk, a period with average annual temperatures below –2°C occurred during the period from 1873 to 1920 (Cappelen 2005). Other factors could also have influenced the mass balance of the glacier, but it is possible that the glacier did not respond until around 20 years after the onset of cooling.

Pronounced moraines referred to the 1920 stade can be followed for 16 km from Isvand to the glacier front, which at that time was located in Kangersuneq fjord, *c.* 12 km behind the Little Ice Age maximum position (Fig. 12). The location of the glacier margin in Isvand between the positions in 1888 and 1936 also implies an approximate culmination of this event *c.* 1920.

1920–1985: This period shows an increasing rate of recession beginning in 1920 and culminating *c.* 1955–1968 with a rate of *c.* 70 m per year. The recession rate fell to 12 m per year between 1968 and 1985. This pattern may reflect the temperature history in the region (Cappelen 2005). The temperature record at Nuuk shows that there was a broad maximum in mean annual temperatures around 1930, followed by slowly decreasing temperatures until *c.* 1960. The time period from 1960 to 1990 was characterised by fluctuating low temperatures.

1985–2010: The distance between the outer part of the trimline zone and the ice margin is rather stable at *c.* 5.5 km from the Little Ice Age maximum extent (Fig. 9B). Satellite images indicate that the shrunken Isvand lake in the first decade of the 2000s have drained through Kangiata Nunaata Sermia. This happened on two occasions, around 2004 and 2009. Thus after at least *c.* 250 years, the drainage of lake Isvand to Ameralla has changed back to the medieval conditions of the area with a very modest water discharge through Austmannadalen (Weidick & Citterio 2011).

The Kangiata Nunaata Sermia glacier system

Conditions around the head of Kangersuneq fjord after the time of the Norse settlers cannot be described better than by Roussell (1941, p. 16–18), who after a description of Ameralik and Austmannadalen writes about Kangersuneq: *This is the great fjord, now called Kangersuneq, which from the innermost part of the settlement cuts its way southeast towards the Inland Ice and embraces three glaciers, one of which is dead whereas the other two are very active, even if their calves are only small in comparison with those of North Greenland. All the same, their production is large enough to prevent the fjord from being navigable even to small craft. It is said that the chances of getting through are best in the month of August; one year at this time we succeeded with great difficulty in forcing a boat half way up the fjord, where we had to go ashore and continue on foot. Another year we arrived a little earlier, but the fairway was closed. Considering that along the east shore there are several farms, and not the smallest either, it must be assumed that conditions in the Middle Ages were different. On the other hand one cannot be too careful when summing up natural conditions in Greenland. In the same fjord it is clearly to be seen that the principal glacier once* *extended much farther out (fig. 8); the lower part of the rock sides is as it were divided into two parts along a line which slants evenly down from the present upper edge of the ice to the water about 10 km down the fjord. Above this line the fells have the usual brownish-green vegetation, but below it they are bare and barren, as if the ice had left them only recently. Now, there are ruins inland behind the place which would then have been the front margin of the glacier, which seems somewhat incredible; can it be, then, that in the time between 1360 and now the glacier advanced and then retreated? A photograph taken by Rink (National Museum archives) in the 1850s shows that the conditions were exactly as they are today. And one is tempted to say that if eighty years cannot spread the vegetation, the situation may just as well be eight hundred years old.*

The fjords then as now were the main lines of communication for the settlements, and no one left the waterside of his own free will. Nevertheless, in both the Vatnahverfi of the East Settlement and to some extent in the West Settlement there are farms lying several hours' journey from the landing place (fig. 9), and accordingly this must be taken as evidence of the extraordinary intensity of the settlement. In the West Settlement there is the possibility that these inland farms were those of the last remnants of the tribe, who in these remote regions tried to find peace from the Eskimos. This, however, has been disproved with complete certainty by the excavations in the Austmannadal. The fairly rich finds of artefacts were of exactly the same types as those unearthed in the main farms by the fjord, and the bones in the refuse heaps show that even inland the large marine mammals were an important economic factor, which means that the farmers in the valley cannot have concealed themselves, but must often have gone whaling and sealing out through the fjord to the open sea.

The photograph mentioned as fig. 8 in this quotation shows ruin group 16 and the trimline zone on Akullersuaq semi-nunatak, seen from the north. The photograph by Rink mentioned in the text is also shown here (Fig. 13A). Roussell's fig. 9 shows an inland Norse farm in the innermost part of Austmannadalen. The Eastern Settlement refers to the Norse settlements in South Greenland and the Western Settlement to the Norse settlement in the Godthåbsfjord region. Little is known about the innermost parts around Kangiata Nunaata Sermia from the 18th century. On Thorhallesen's map from 1776 (Fig. 10; Thorhallesen 1914) two large outlets are seen coming from the Inland Ice and calving in Kangersuneq. The northern of these outlets must be Narsap Sermia and the southern is the Kangiata Nunaata Sermia glacier system, consisting of Kangiata Nunaata Sermia and Akullersuup Sermia.

K.L. Giesecke described the area around the head of Kangersuneq, which he visited in August 1808, mentioning the place names Nunatarsuaq and Illorsuit. He may have camped between Illorsuit (ruin group 13a; Fig. 7) and ruin group 15 (at Umiivik). Giesecke (1910, p. 150) described the ruins as stone heaps, traces of stone walls and single buildings, covered with soil, grass and bushes.

The following description of the Norse ruins at Saqqarsuaq is more detailed (ruin group 16, Figs 3, 7). On older maps, ruin group 16 is located on the north-western slope of the valley between Qamanaarsuup Sermia and the inner part of Kangersuneq, *c.* 5 km from the icefjord (Figs 3, 7). Roussell (1941, p. 78, fig. 54) and Kort & Matrikelstyrelsen (1993), however, placed ruin group 16 near the southern tip of the semi-nunatak Nunatarsuaq, near the coast of Kangersuneq. According to his diary for 7–12 August 1808, Giesecke (1910, pp. 147–151) passed Narsap Sermia and Narsaq on his way to the head of Kangersuneq and then camped close to Narsaq due to bad weather. The following attempt to reach the front of Kangiata Nunaata Sermia glacier system took place on 12 August, when Giesecke and his companions arrived at the Illorsuit site (ruin group 13a, Figs 3, 7), described as being located at the end of Kangersuneq. They reached ruin group 16 (Saqqarsuaq) in the valley between Qamanaarsuup Sermia and the frontal parts of Kangiata Nunaata Sermia. Giesecke wrote (pp. 150–151) the following about the valley, the glaciers and the ruin group: *This valley runs to the opposite side back down to the sea, and has as the former in its centre a large raging mountain river. Part of it runs straight to the sea, and part of it runs via another curvature around a small mountain towards the glacier to the east.*

This glacier is larger, steeper and more dangerous than the one to the north-east, and there are no nunataks, one sees only the immense masses of towering ice. Here, very close to the ice, I found a well-preserved Norse ruin that protruded above the small shrubs. It formed a square and measured close to 50 × 50 feet, and in some places the walls reached c. 1 yard [1 m] above the moss, grass and shrubs. The inner walls were difficult to discern, but the shrubs indicated three main rooms. Several other buildings in this rocky valley were probably buried below the glacier long ago.

I ascended both mountains located between the described valleys in the area. These mountains are extremely fissured; the fissures are sometimes 1 fathom [2 m] or more wide and very long. The surface of the mountains is covered by enormous rock fragments, which indicates a fairly recent

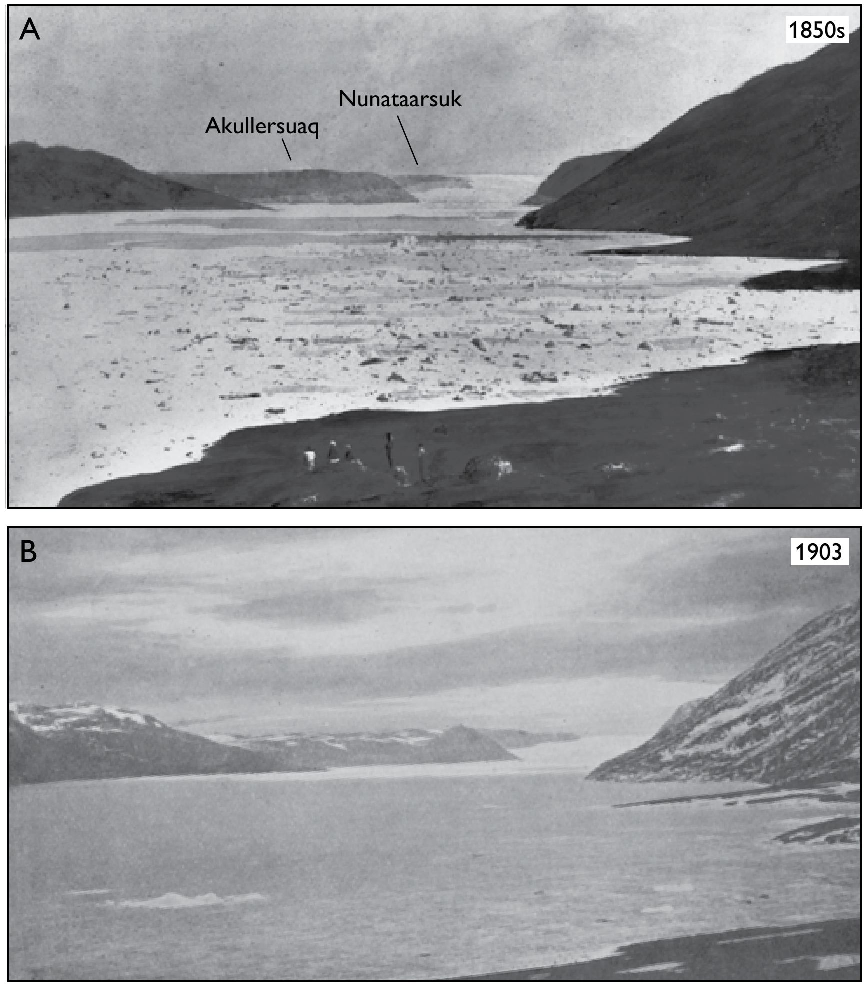

Fig. 13. **A**: The front of Kangiata Nunaata Sermia, seen from the north. The photograph was taken in the 1850s by H. Rink; it is housed in the archives of The National Museum in Copenhagen. **B**: Same as above, taken by John Møller in 1903. Reproduced from Bruun (1917, fig. 11, p. 76). The location of the photographer was not exactly the same as for **A**. H. Rink (1819–1893) was a royal inspector of South Greenland and later a director of the Royal Greenland Trade. In addition to his administrative duties, he is known for his pioneering studies of the geology, glaciology and anthropology of Greenland. J. Möller (1867–1935) was born in Greenland and educated in Denmark as a printer, photographer and interpreter.

earthquake, because the rock fragments, which here and there fit together are still very sharp. On the other side of the valley, towards the glacier, a large lake is found, which drains over a bedrock threshold to the glacier and on to the sea. In the valley near the lake some reindeer grazed quietly until I was around fifty paces away...

Giesecke described the view from the mountain (*c.* 1000 m above sea line): *From the higher of the aforementioned mountains I could see Pisissarfik, a part of Ameraglikfiord with its small islands, as well as both glaciers in this region. The glaciers actually belong to the great ice cover that is found on all land from north-west to south-east. The sight of this ice cover is incredibly beautiful, and well worth the difficult ascent.* (Authors' translation.) 'Pisigsarfik' was the fjord that is now called Kapisillit Kangerluat; the name Pisissarfik is now used for a 1220 m high mountain peak on the northern shore of this fjord.

Following the descriptions above and a later description by Roussell, the location of ruin group 16 near Kangersuneq can be determined. The presence of a large ice-dammed lake filling the valley in front of Qamanaarsuup Sermia must imply an advanced position of the Kangiata Nunaata Sermia system. The general description also indicates that the front was close to ruin group 16, and that the glacier dammed the meltwater from Qamanaarsuup Sermia to form an ice-dammed lake (called 'Saqqarsuaq lake' in the following). Knuth (1944, p. 100) doubted that Giesecke had visited ruin group 16, which he suggested should be located farther to the east in accordance with D. Bruun's map (Fig. 7). However, Roussell's description of ruin group 16, and Roussell's localisation of ruin group 16 to a position close to the eastern margin of Kangiata Nunaata Sermia based on the description of Giesecke, fits with Roussell's own measurements of the ruin group.

Kleinschmidt's map from 1860 (Fig. 11) shows the front of Kangiata Nunaata Sermia in a more retracted position than described by Giesecke in 1808, when Kangia-

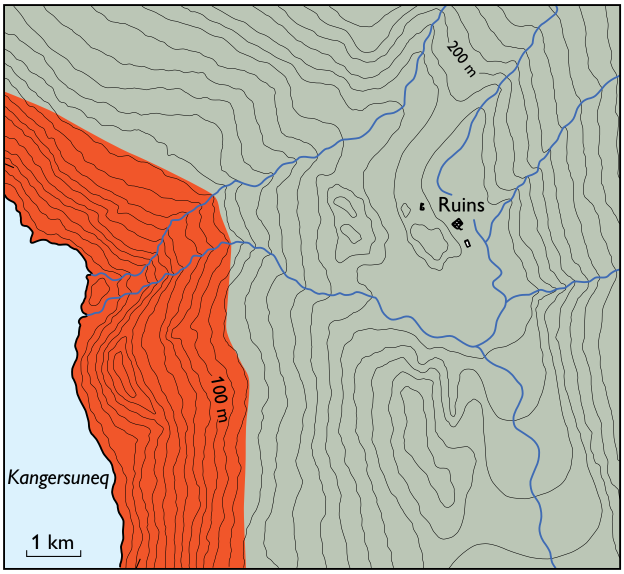

Fig. 14. Ruin group 16 and the surrounding terrain at Saqqarsuaq, Kangersuneq icefjord. Redrawn from Roussell (1941, fig. 54). The red part of the terrain indicates the estimated extent of the ice cover of Kangiata Nunaata Sermia at its maximum during the Little Ice Age. The slope of the trimline zone maximum is c. 20 m/km, decreasing towards the north. According to Roussell (1941), the altitude of the trimline zone is 123 m a.s.l., and the ruins are at 208 m a.s.l., although the latter figure is not in accord with the contours on the map. Note that this is a reproduction of the original map.

ta Nunaata Sermia blocked the valley to Qamanaarsuup Sermia leading to the formation of an ice-dammed lake. On Kleinschmidt's map the glacier front is placed south of the Akullersuaq semi-nunatak, 10–12 km from the Little Ice Age maximum position as shown by the trimline zone. The same position is shown on J.A.D. Jensen's map from 1885.

The earliest photograph of a glacier in Greenland may be that taken by Rink in the 1850s. Rink's photograph shows the front of Kangiata Nunaata Sermia, seen from the west side of Kangersuneq at the isthmus between Kapisillit Kangerluat and Kangersuneq, north-east of the Kapisillit settlement (Fig 6B). Rink's photograph, which is also mentioned by Roussell (1941, p. 17), is reproduced here (Fig. 13A). A later photograph taken from approximately the same position by John Møller in 1903 and published by Bruun (1917, fig. 10, p. 76) is shown here as Fig. 13B. The trimline zone on the mountain walls of the semi-nunataks Nunataarsuk and Akullersuaq can be seen and the position of the glacier front on both photographs can be estimated to 10–12 km south of the Little Ice Age maximum extension of the glacier. Following a visit in 1909, Nordenskiöld (1914, p. 638–639) wrote that Kangiata Nunaata Sermia had been retreating, in contrast to Narsap Sermia which was advancing during the first years of the 1900s. Concerning ruin group 16 at Saqqarsuaq, Bruun (1917, p. 78) wrote that he was told by Greenlanders during his visit in 1903 that there was a rather small ruin, but earlier there could have been more ruins, which may have been flushed away by a river or destroyed by the ice. Both Bruun's and Nordenskiöld's evidence for recession of Kangiata Nunaata Sermia could refer to the middle or the last decades of the 1800s, and the advance leading to the 1920 stade may have started in the last decades of the 1800s or the beginning of the 1900s.

The older Little Ice Age maximum advance seems therefore to have occurred in the 1700s and Giesecke's description of a lake in the valley between Qamanaarsup Sermia and the Kangiata Nunaata Sermia glacier system implies a situation with the front of the Kangiata Nunaata Sermia glacier system close to the Little Ice Age maximum extent. Bruun's record of other ruins at the site of ruin group 16 being removed by the nearby glacier or flushed away by its marginal drainage is easy to understand if it occurred during the maximum extent of the Kangiata Nunaata Sermia glacier system. According to the trimline zones, the glacier in this area at its Little Ice Age maximum reached an elevation of 123 m a.s.l. (Roussell 1941, p. 79). The present ruins are located at 208 m a.s.l., according to Roussell's description of the ruin site (Roussell 1941, fig. 54, p. 78), which is indeed close to the trimline zone (Fig. 14). The apparently fairly stationary

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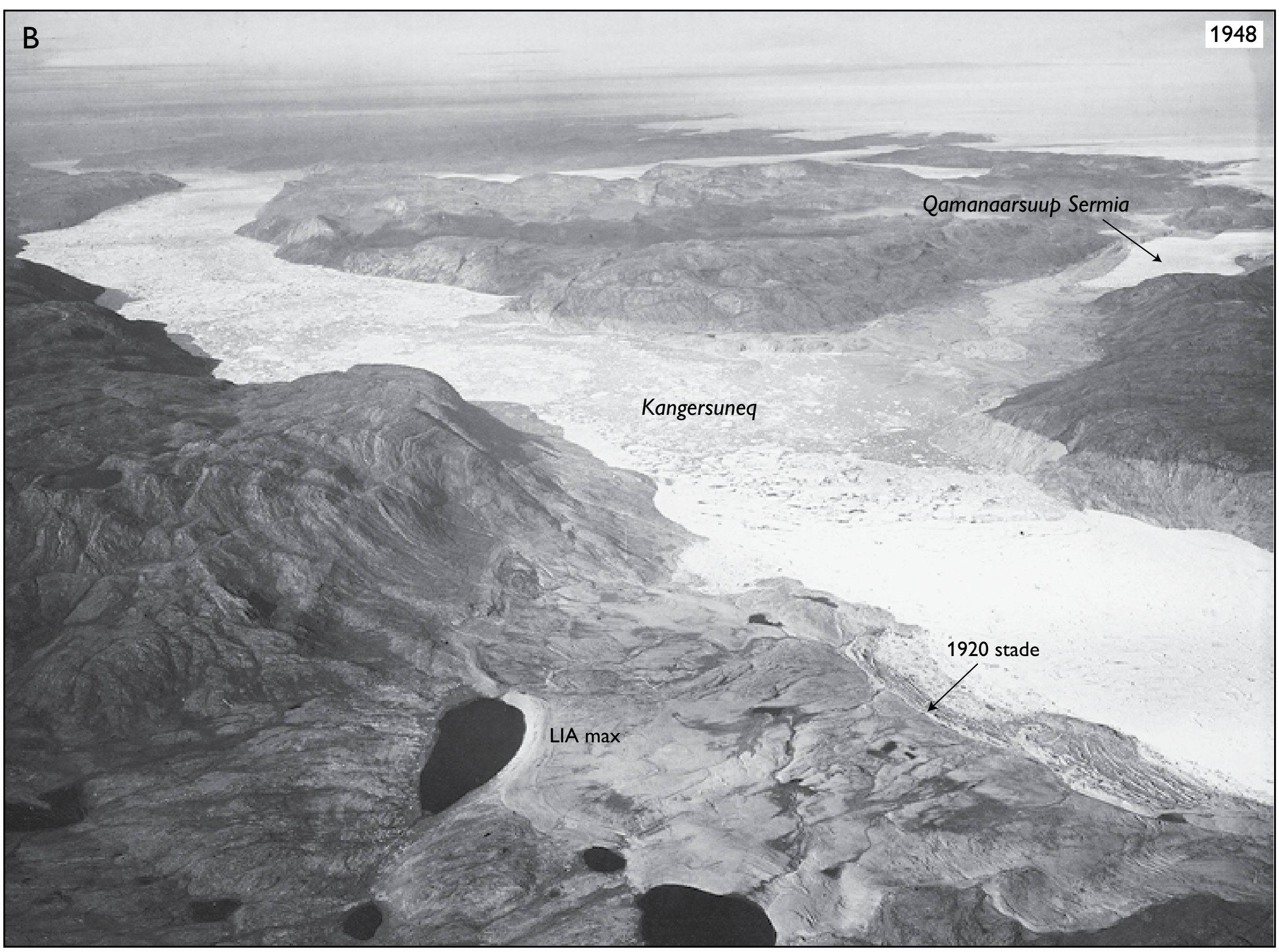
Fig. 15. **A**: Front of Kangiata Nunaata Sermia in 1921 seen from the west. Photograph by Aa. Nissen in GEUS' glaciological archive (filed under glacier 1CH23003); Aage Nissen (1889–?) was a teacher at and later a leader of the Teacher's College in Nuuk in the period from 1920 to 1927. **B**: Oblique aerial photograph of the interior part of Kangersuneq looking from the south-west over Kangersuneq to the north-east, where the front of Qamanaarsuup Sermia can be seen, surrounded by a broad trimline zone. In the foreground a double set of marginal moraines can be seen. The outer set (labelled **LIA max**) marks the extension of the Kangiata Nunaata Sermia glacier system in the 1700s. The younger set (labelled 1920 stade) marks the maximum of a large readvance, presumably initiated during the beginning of the 1900s and culminating shortly before 1920. Geodetic Institute, route 506B-N, no. 6270, 21 August 1948.


A
1921


B
1948
Qamanaarsuup Sermia
Kangersuneq
1920 stade
LIA max

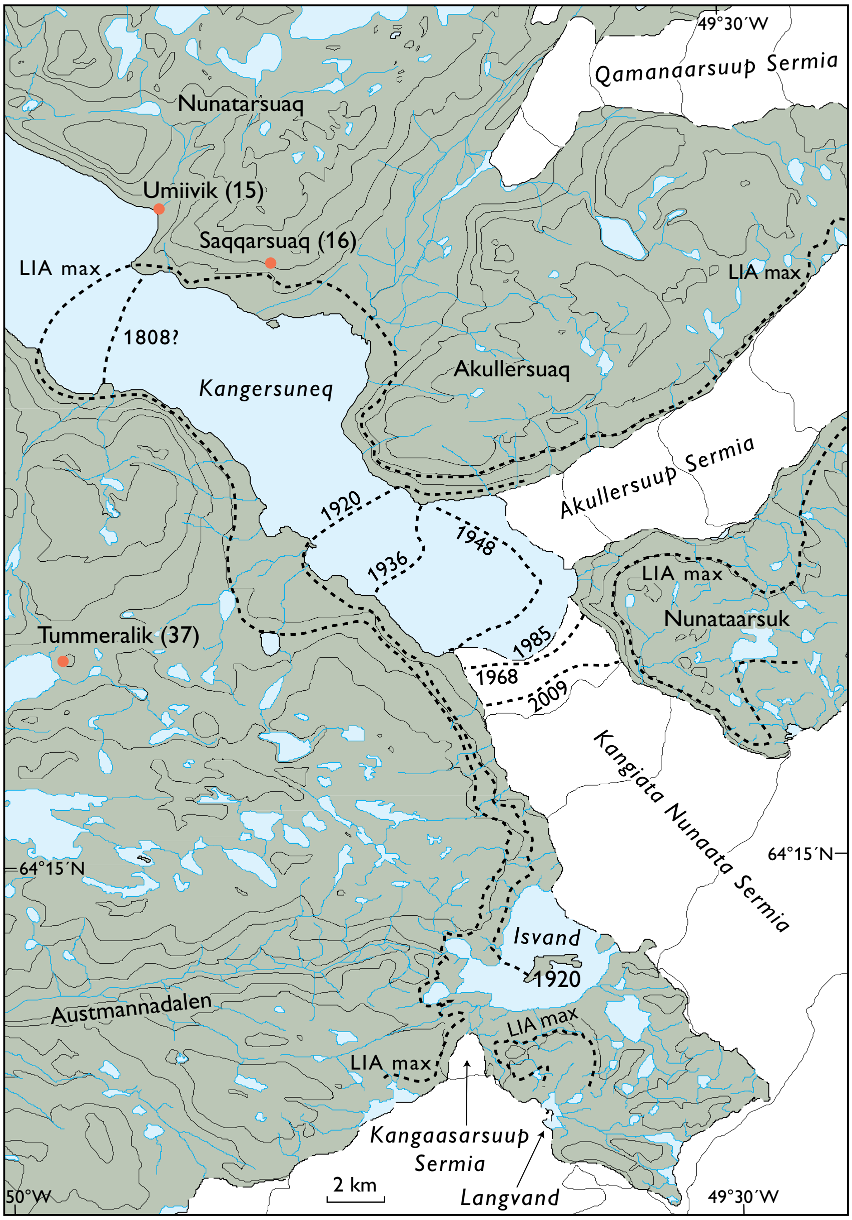


Fig. 16. Recession of Kangiata Nunaata Sermia since the Little Ice Age maximum (**LIA max**) in the 1700s. The oldest ice margin known after the LIA max is the presumed position of the glacier front in 1808, when the glacier prevented water from draining from the Qamanaarsuup Sermia glacier to the Kangersuneq fjord. During later positions from c. 1850 to the 1930s, the front was located somewhere between the southern tip of the Akullersuaq semi-nunatak in the north-east and the area east-north-east of Tummeralik (ruin group 37) in the south-west. Umiivik: ruin group 15, Saqqarsuaq: ruin group 16. The map is based on aerial photographs from 1985 when the ice-dammed lake Isvand was at its maximum extent.

glacier front at the end of 1800s and beginning of the 1900s astonished Roussell (see quotation on pages 23–24). He estimated the front of Kangiata Nunaata Sermia to be *c.* 10 km from its Little Ice Age maximum position, indicating a century of 'stability' of the position of the glacier front. However, the large fluctuation during the 1920 stade must have taken place during this period.

With respect to ruin group 15 (Umiivik), Bruun (1917, p. 78) referred to the statement of the Greenlanders, viz. that it is a locality with many, partly overgrown ruins, which is in accordance with information from a visit to the place by O. Bendixen in 1916 (mentioned in Bruun 1917, p. 72). As mentioned above, J.A.D. Jensen's map was widely used up to the 1930s. A photograph from 1921 shows the front of Kangiata Nunaata Sermia seen from the north-west (Fig. 15A). The glacier front is located close to the moraines that formed during the 1920 stade.

During the first decades of the 1900s, ice-margin features formed in the central parts of the trimline zone (Fig. 15B). These ice-margin features are widespread and dark in several places, which imply dead ice or ice-cored moraines. Traces of this advance (the 1920 stade) are also seen at Isvand.

A more general recession began in the 1920s, but on aerial photographs from 1948 Kangiata Nunaata Sermia and Akullersuup Sermia are still confluent, forming a 'Kangiata Nunaata Sermia glacier system' where the glacier tongues have a common front in Kangersuneq. Not until the end of the 1940s was the recession so pronounced that the glaciers were split up into two separate outlets. According to a satellite image from 22 June 2009 (Figs 12, 16), continued recession has brought the front of Kangiata Nunaata Sermia to a position 21–22 km behind the position of the Little Ice Age maximum in the 1700s. During the period from 1985 to 2010, the front of Akullersuup Sermia has only retreated 1–2 km.

Evaluation

The sources from the 18th century all describe an advancing glacier. The front of calving tidal glaciers may show both annual fluctuations of up to a kilometre, with advance during the winter and retreat during the summer, and larger decadal fluctuations. The historical record can provide information about the latter, but usually only give general trends, and only rarely contribute with accurate data.

The Little Ice Age maximum extent was presumably reached for the first time in the beginning of the 1700s, but as some sources also speak about advance later in that century, it is possible that the ice margin was close to the Little Ice Age maximum throughout the century, although with minor fluctuations:

***c.* 1775–1810:** The frontal advance of the Kangiata Nunaata Sermia glacier system may have culminated near a headland in Kangersuneq, located just south of the ruin group at Umiivik (Qassertup Nuua). Thorhallesen's map from 1776 gives little information but the glacier at the head of what is called 'Ujaraksoak fjorden' on the map must be the Kangiata Nunaata Sermia glacier system. This map shows the length of Kangersuneq fjord from the mouth at Karra (Fig. 3) to the head of the fjord at the Little Ice Age maximum of the Kangiata Nunaata Sermia glacier system to be about 6 miles; since 1 Danish mile is 7.5 km (Norsk Forlishistorisk Forening 2012; Marcussen 2011), this equates to *c.* 45 km, a distance that is compatible with modern maps (e.g. see Fig. 3).

The overall advance ended in the 18th century, and was followed by a slow recession that may have continued to the beginning of the 19th century, when the Kangiata Nunaata Sermia glacier system still blocked the valley to Qamanaarsuup Sermia. The 'Saqqarsuaq ice-dammed lake' existed in the beginning of the 1800s, implying that *c.* 1808 the glacier front was still close to the maximum extent of the Little Ice Age, which can be mapped from the well-defined trimline zone (Fig. 14).

1810–1860: During the following decades, fast recession took place, so that the front at the latest around 1860 had retreated *c.* 10–13 km from the Little Ice Age maximum extent. During this *c.* 50 year period of recession, the average recession rate was 200–260 m per year.

The information from Giesecke about an ice-dammed lake (the 'Saqqarsuaq lake') between Kangiata Nunaata Sermia and Qamanaarsuup Sermia in 1808 and the short distance (*c.* 5 km) from the Little Ice Age maximum of the frontal parts of Kangiata Nunaata Sermia to the 'Saqqarsuaq lake' must imply a glacier dam by a large ice body (Fig.17A). Roussell (1941, p. 79) measured the maximum height of the trimline zone at ruin group 16 (Saqqarsuaq) to have been 123 m a.s.l., i.e. close to the lake. The exact lake level is unknown, but it was presumably *c.* 48 m a.s.l. (Fig. 17A). The damming ice body can scarcely have had a much smaller thickness than at the Little Ice Age maximum, and we therefore suggest that the glacier front in 1808 still had a position close to the maximum of the glacier system.

As mentioned in the introduction, depths over 600 m are found in the inner part of Nuup Kangerlua. Off Kapisillit, the bottom of Kangersuneq is flat at *c.* 340 m, and no indication of a submarine threshold or moraine is observed that may have been formed during the Kapisigdlit stade. In contrast, ice-margin deposits from the Little Ice Age maximum form a threshold at 150 m below sea level (b.s.l.). The 1920 stade is only marked by a small rise of the sea bottom to a depth of *c.* 300 m. It is possible that both thresholds were anchoring points for the front for longer periods, but it is not known if the thresholds consist of bedrock or ice-margin deposits (Fig. 8).

The increase of ice in Kangersuneq before 1885 (J.A.D. Jensen 1889, p. 88) could have been connected to a large breakup during the thinning of the outermost part of the Kangiata Nunaata Sermia glacier system. As large calf-ice production may be a sign of a retreating glacier rather than an advancing glacier, the increased calf-ice production could indicate a period with fast recession in the first half of 1800s.

1860–1903: Information from 1850 and the following decades are based on the map of Kleinschmidt, and

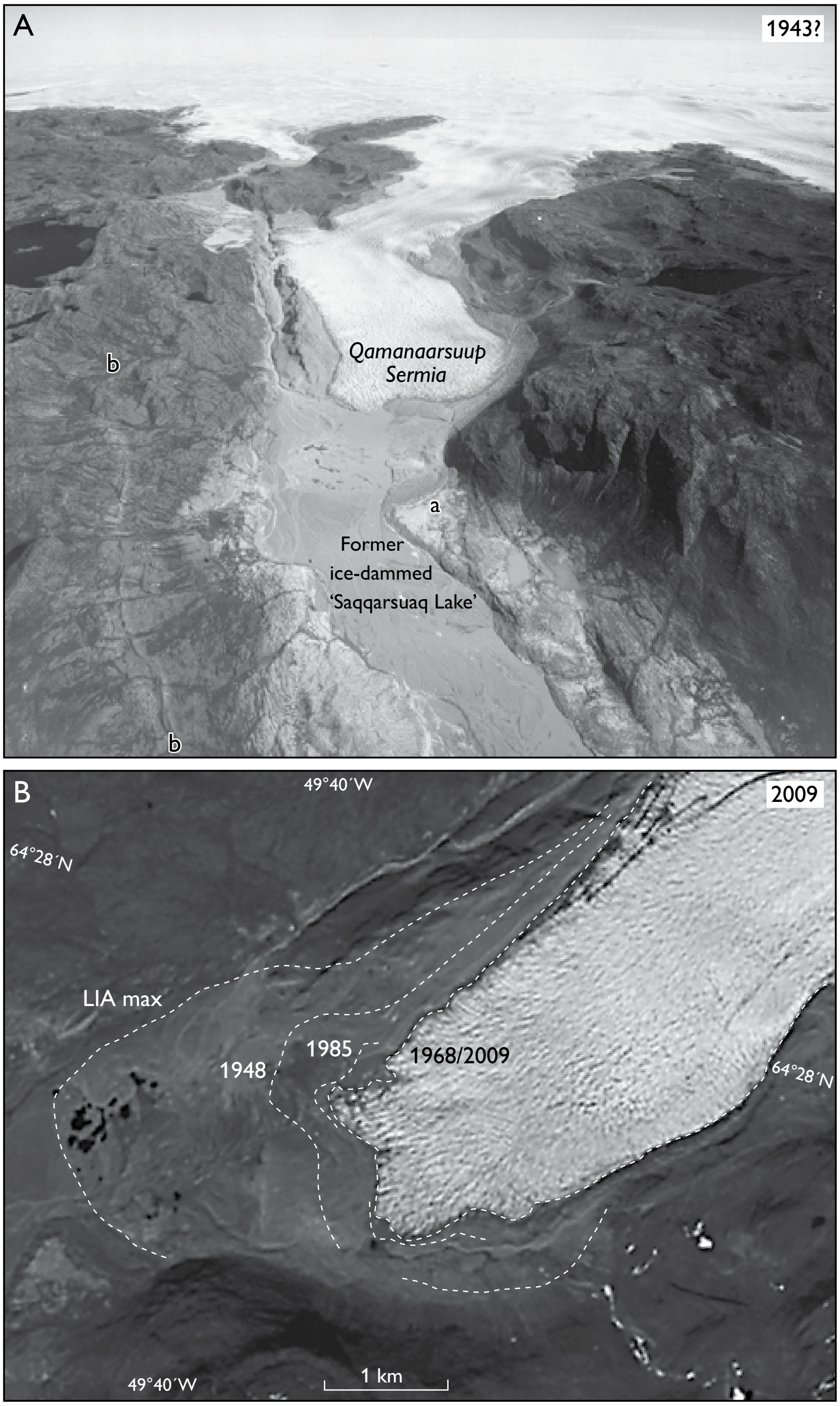


Fig. 17. **A**: Qamanaarsuup Sermia, seen from the west. In the foreground near the front of the glacier a proglacial lake terrace (**a**) is seen. It is presumably related to the ice-dammed 'Saqqarsuaq Lake', that occupied the valley between Qamanaarsuup Sermia and Kangersuneq until the beginning of the 1800s, as observed by K.L. Giesecke in 1808 (Giesecke 1910). **b–b** marks a moraine ridge that may be referred to the Kapisigdlit stade (tentatively dated to 8.2 ka BP). Aerial photograph, Geodetic Institute, route 505 E-Ø, no. 7418 (probably from 1943). **B**: Qamanaarsuup Sermia with frontal positions at the Little Ice Age maximum, in 1948, 1968 and 1985 according to Taurisano (2004, fig. 3.5), plotted on an ASTER image from 2009.

Rink's and Møller's photographs from the 1850s and 1903. They indicate that the glacier front, at least at these specific times, was located at a position 10–12 km from the Little Ice Age maximum, as also suggested by Aa. Roussell.

1903–1920: Only little information is available from the first two decades of the 1900s. Although it could seem that the front was essentially stable from *c.* 1850 to *c.* 1920, however, significant changes in the frontal position must have occurred during this period. A photograph by Aa. Nissen from 1921 (Fig. 15A) shows the front of the Kangiata Nunaata Sermia glacier system. The glacier front was close to, but behind the moraines of the 1920 stade, and the 1921 glacier front was closely surrounded by fresh moraines deposited just prior to 1921. The moraines are the result of a marked advance, presumably initiated one or two decades before. The ice-margin features can be seen in the trimline zone on the west side of Kangiata Nunaata Sermia, extending from an altitude of around 400–450 m a.s.l. in the Isvand area (*c.* 15 km from the front) and down to the calving front in Kangersuneq fjord. A large initial recession must have taken place before *c.* 1900, but how far up the Kangersuneq fjord is not known. The following advance probably occurred during the first two decades of the 1900s.

A clear colour difference is seen between the trimline zone below and above the line of the 1920 stade on photographs and satellite images (Fig. 9B). The upper and older part of the trimline zone, which is from the 1700s, is characterised by widespread lichen and vegetation cover, as well as some soil development. The lower and younger part of the trimline zone was not left finally by the glacier until after *c.* 1920, and this part is therefore more barren than the older part. However, both parts can be characterised as 'barren ground' that is clearly different from the surrounding areas with older vegetation.

1920–1985: A period of fast recession of the front took place after *c.* 1920. Around 1950–1960, this led to a separation of the Kangiata Nunaata Sermia glacier system into the Kangiata Nunaata Sermia proper and Akullersuup Sermia, which is now a separate outlet from the ice sheet. The later development of the frontal position of Kangiata Nunaata Sermia is shown by the following estimated positions of the front behind the Little Ice Age maximum: 1920: 11.5 km, 1921: 11.8 km, 1936: 14.5 km, 1948: 18 km and 1968: 20.5 km (Fig. 16). An advance took place in the following years and in 1985 the front had advanced to a position *c.* 20 km behind the Little Ice Age maximum, as also pointed out by Timm (2010).

1985–2010: By 2009, the front of Kangiata Nunaata Sermia reached a position 22 km behind the Little Ice Age maximum. According to a 2010 ASTER image, however, it had advanced to a position *c.* 20.5 km from the Little Ice Age maximum. These secondary fluctuations of the frontal position during the last decades presumably reflect minor annual fluctuations of the glacier, the frontal position of which is determined by anchor points such as submarine thresholds or other features of the fjord topography (e.g. Mercer 1961).

Regarding the recession of Akullersuup Sermia, we note that the height of the trimline zone above this glacier also indicates a marked thinning, as recorded for Kangiata Nunaata Sermia. After the split of the glacier system, the front of Akullersuup Sermia has receded only *c.* 2 km between 1985 and 2010.

Qamanaarsuup Sermia

This glacier has already been mentioned above in connection with the formation of the ice-dammed 'Saqqarsuaq lake' in front of the glacier (Fig. 17A). Its more recent development is described below. The glacier and its surroundings are located in the most remote part of the Kangersuneq region. Although its name refers to reindeer hunting (qamavoq = wait for it), it must have been difficult to access during the Little Ice Age maximum in the 1700s when the valley in front of it was closed by the 'Saqqarsuaq lake' and the Kangiata Nunaata Sermia glacier system. Hence the first information about this glacier and the valley in front of it was published following the mapping by J.A.D. Jensen in 1885 (Jensen 1889). The glacier is now surrounded by a trimline zone, the outermost parts of which appear to be related to the proglacial, ice-dammed lake that may have existed in the 1700s.

Morphological evidence of a former ice-dammed lake was also reported by Andsbjerg (1985). This lake may have drained in the first half of the 1800s, but a more complete understanding of the history of this lake must be left to future investigations of the lacustrine deposits in the valley.

The oldest aerial photograph that covers Qamanaarsuup Sermia dates from 27 August 1936 (Geodetic Institute route 61A, no. 25283, not shown). Unfortunately, this oblique photograph was taken from a distance and the glacier lobe can only be faintly seen surrounded by a trimline zone.

Taurisano (2004) puts the last advance to the Little Ice Age maximum at 1880–1890 on the basis of the lichenometrical dates of Beschel (1961). However, Beschel's data do not preclude that the maximum position was reached earlier, in the 1700s. Beschel's data on growth rates of lichens are from central West Greenland, far from the Kangersuneq region, and are mainly based on fluctuations of local, small glaciers. Subsequent frontal positions of Qamanaarsuup Sermia between 1948 and 1993 were mapped by Taurisano (Fig 17B; Taurisano 2004, fig. 3.5).

From the Little Ice Age maximum to 1948 the glacier receded 1.5 km, corresponding to an average value of 24 m per year, if recession began in 1885 as suggested by Taurisano. From 1948 to 1968, the glacier receded 0.5 km, corresponding to 25 m per year. Between 1968 and 1985, recession was very limited. From 1985 to 1993, the glacier front receded *c.* 100 m, corresponding to 13 m per year. Finally, on a Landsat image from 2009 the front was at approximately the same position as in 1993.

On the basis of aerial photographs from 1968 and 1980, detailed maps (1:10 000, contour interval 10 m) were made by Knudsen (1983). From a comparison of the two maps, Knudsen concluded that the glacier had receded 25–50 m and he recorded a thinning near the snout of the glacier to less than 10 m. The contour lines at higher elevations were nearly identical in the two years.

Evaluation

Little is known about the fluctuations of this glacier before the 1900s. Its frontal deposits at the former ice-dammed lake may indicate that the maximum extent of the glacier and the formation of the ice-margin deposits took place at the same time as the possible formation of the lake, so that the history of this glacier may be similar to that of Kangiata Nunaata Sermia. However, the later recession of this land-based glacier so far only amounts to around 2 km. During the more detailed measurements of the changes of this glacier between 1968 and 1985, the recession was only 25–50 m, i.e. 1–3 m per year. The presumed ice-dammed lake ('Saqqarsuaq lake') must have been emptied during the recession between 1810 and 1850. The terrace in Fig. 17A marked 'a' may be a remnant of the alluvial plain that formed during the Little Ice Age maximum; the surface of the terrace would thus mark the level of the former 'Saqqarsuaq lake' at its maximum extent. The elevation of the terrace was measured by GPS in the summer 2011 to be 48 m a.s.l. (Dirk van As, personal communication, 2011), which must indicate the maximum elevation of the lake level. Because the elevation of the former lake bottom is 0–30 m a.s.l., the lake must have been shallow even though it had an extent of *c.* 10 km^2.

Observations of the frontal positions of Qamanaarsuup Sermia in 1948, 1968 and 1993 (Taurisano 2004) show positions of 1.5, 2.0 and 2.1 km behind the Little Ice Age maximum, respectively, and indicate that the recession rate began to decrease in the 1960s, possibly induced by a minor cooling of the climate. According to a Landsat image, in 2009 the frontal position was close to that of 1993, as mapped by Taurisano (Fig. 17B).

According to Taurisano (2004, pp. 36–39), the lower and upper parts of Qamanaarsuup Sermia showed marked differences in surface elevation changes from 1968 to 1985. The upper part thickened by 1 m per year whereas the lower part thinned by 0.3 m and is gradually being transformed into dead ice (see frontispiece).

Narsap Sermia

The surroundings of Narsap Sermia have been described several times due to the occurrence of Norse ruins (groups 11 and 12; Figs 3, 7) near the front of Narsap Sermia (Figs 3, 7, 18). Early records of these ruins are from Bruun (1917, pp. 75–77), who included information from O. Bendixen from a journey in 1916 and from Greenlanders who noticed these ruins close to the front of the glacier.

Narsap Sermia was plotted on the early map by Thorhallesen (Fig. 10). Although his map is sketchy and does not depict ruin sites in this area, the glacier front is, as today, shown at some distance from Kangersuneq. This is in contrast to the more northern fjord, on his map called 'Naviangoæt', where the Norse ruin groups 7 and 8 are located (Figs 3, 7).

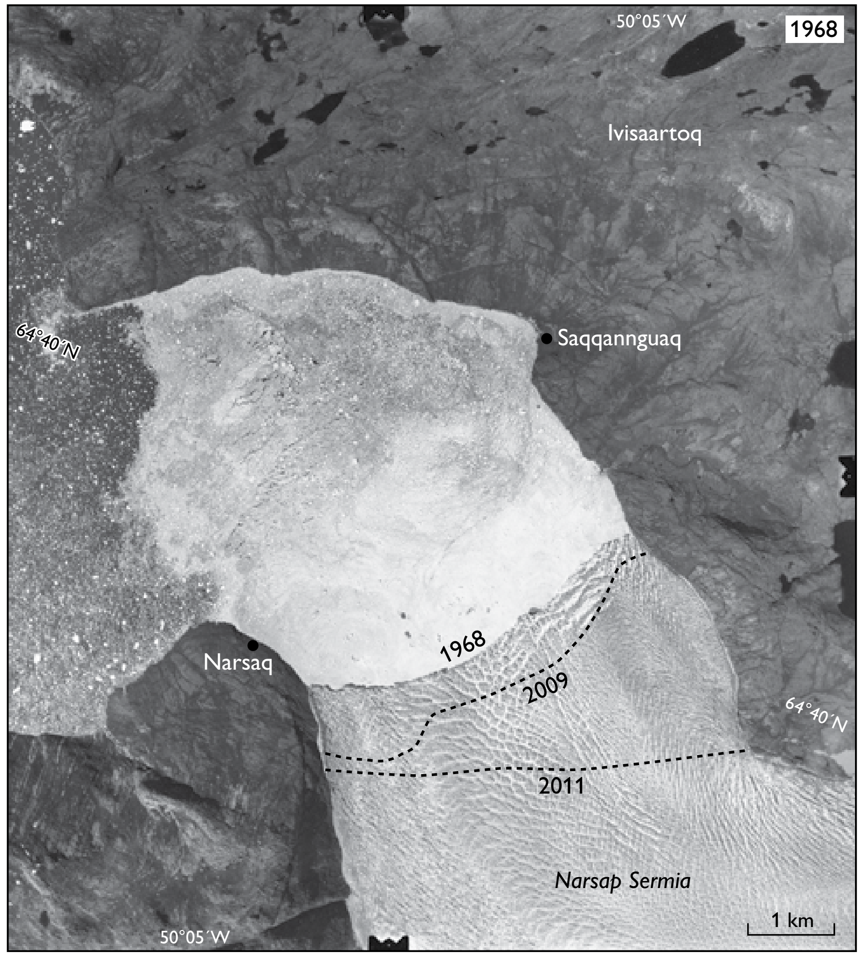
The proximity of the front of Narsap Sermia to Kangersuneq and to Narsaq was also recorded by Giesecke (1910, p. 147–148). On 7 August 1808, he passed its front on the way from Ujarassuit Paavat to Narsaq (ruin group 12, Figs 3, 7), and continued to a place called 'Narkseeitsiaq', where he camped. The camp site must have been relatively close to Narsaq since he described calving noise from the front of Narsap Sermia.

J.A.D. Jensen's map, based on observations in 1884 and 1885, shows a position of the front closer to Kangersuneq. In his description of ruin groups 11 and 12, Jensen does not mention the nearby front of Narsap Sermia (Jensen 1889, p. 110).

From a visit in 1909, Nordenskiöld (1914) reported that Narsap Sermia had advanced during the first years of the 20th century; the advancing glacier had buried several hunting camp sites.

D. Bruun (1917, p. 75) noted, when describing ruin group 11 (Saqqannguaq), that ruins are found at the

Fig. 18. Narsap Sermia. The frontal position of the glacier is taken from a Landsat image from 2009 and drawn on an aerial photograph from 16 August 1968, Geodetic Institute, route 281T, no. 70. In 1968, the Norse ruins at Narsaq and Saqqannguaq were located around 1 and 2.5 km from the glacier front, which is the local Little Ice Age maximum of the glacier. Marked recession of the centre line of the glacier (*c.* 1 km) occurred between 2009 and 2011.



shores of rivulets. This is based on observations by O. Bendixen from his voyage in 1916. For ruin group 12 (Narsaq), D. Bruun (1917, p. 77) reported that at Narsaq, between a steep headland and the end of the glacier, there is a small ruin on the slope immediately above the fjord. Some of the ruins had slipped into the water.

The descriptions of Roussell, after visiting the area in the 1930s, give no new information about Narsap Sermia. Aerial photographs and satellite images from 1936 onwards show that the front of Narsap Sermia has been located at about the same place. It appears that the front of this glacier may have been relatively stable for around 250 years, although this conclusion is based on scattered information. General recession of the glacier front seems to have started in the first decade of this century.

Evaluation

It appears from the map of Thorhallesen (1914; Fig. 10) that the front of Narsap Sermia was situated in a small fjord branch, a short distance from Kangersuneq. The same is seen on aerial photographs from 1936, 1948 and 1985, as well as on satellite images from 2009 and 2011. The glacier is only surrounded by a narrow trimline zone, which supports the proposal that it has not fluctuated much during the past centuries.

Based on studies of aerial photographs and satellite images, Timm (2010) considered the glacier stationary or advancing between 1936 and 1985, but it was suggested that the central parts of the glacier front receded *c.* 700 m between 2002 and 2009. This is in accordance with a narrow trimline zone developed at the lower flanks of the glacier. It appears to be the first signs of the following frontal recession of around 1 km that occurred in the period 2009–2011 (Landsat image, 14 July, 2011), as measured along the centre line of the glacier (Fig. 18).

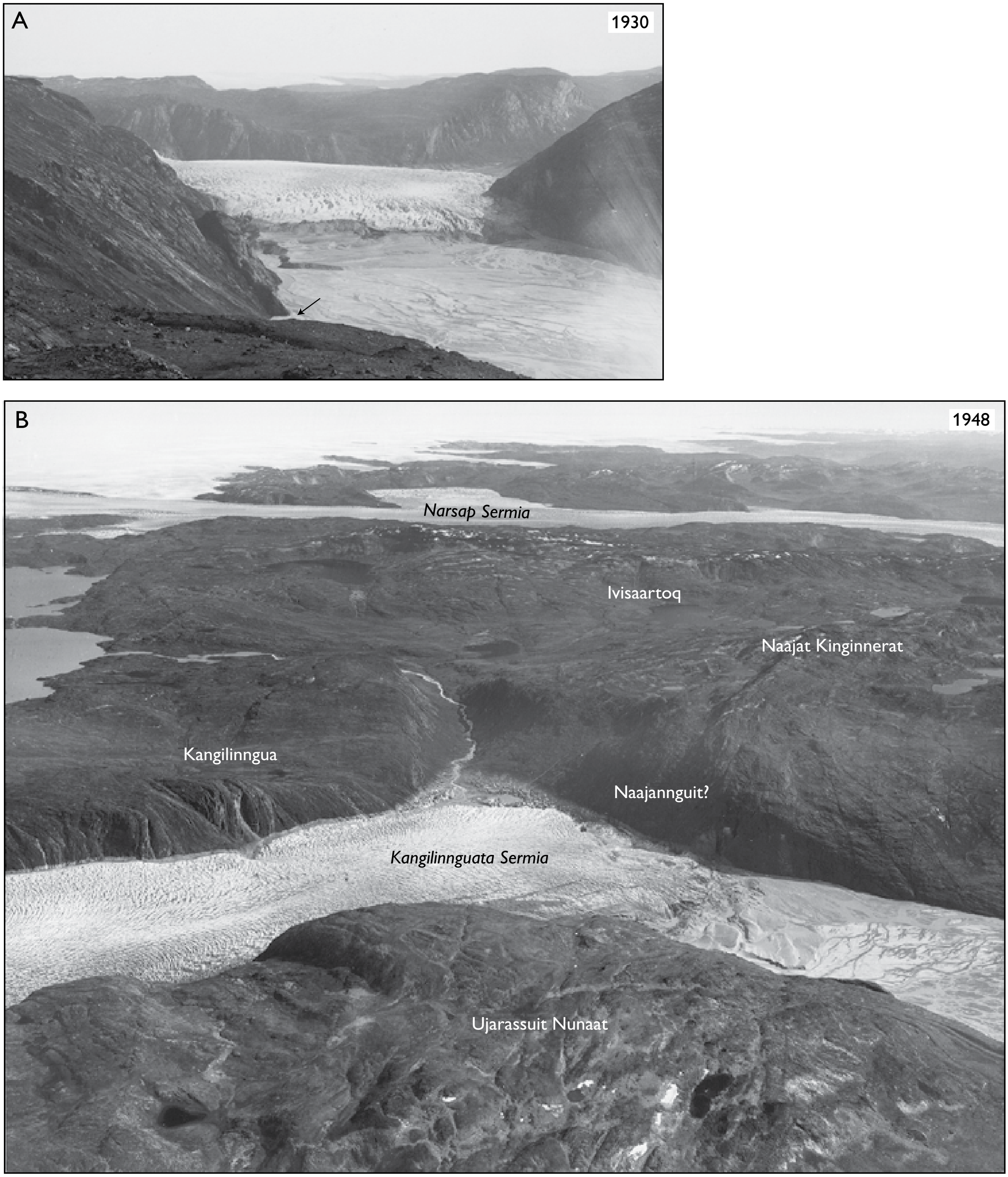


Fig. 19. **A**: Kangilinnguata Sermia on 25 August 1930, seen from a height of 630 m a.s.l. (Gripp 1975, plate 2, fig. 2). The arrow indicates the location of Norse ruin group 8 (Figs 3, 7), which was mapped, described and photographed with the glacier in the background by Roussell in 1934 (Roussell 1941, pp. 76–78). **B**: Kangilinnguata Sermia seen from the north in 1948 (Geodetic Institute, route 505-ES, no. 1948). The lake south of the glacier front (top left) receives large amounts of meltwater from the Inland Ice margin south of Kangilinnguata Sermia. This meltwater drains to the Ujarassuit Paavat fjord, to the right (see Fig. 3) via the outermost part of the front of Kangilinnguata Sermia.

Kangilinnguata Sermia

In contrast to the other outlets around Kangersuneq described above, the interior of Ujarassuit Paavat was described by Hans Egede, who lived in Greenland from 1721 to 1736. His descriptions of the Ujarassuit Paavat fjord region concentrated on a large group of ruins 8 km from the glacier (Ujarassuit; ruin group 7, Figs 3, 7), whereas only few persons have described the more modest ruin group at Puilasoq (group 8, Figs 3, 7), situated only *c.* 2 km from the glacier front. This is because a *c.* 7 km long tidal flat separates the navigable outer part of Ujarassuit Paavat from the inner part of the fjord with the Puilasoq ruin group 8 and the Kangilinnguata Sermia glacier.

E. Thorhallesen seems to have visited the inner parts of Ujarassuit Paavat. On his map from 1776 (Fig. 10), he calls this fjord 'Naviangoæt' and the Ujarassuit site is designated 'Europ. Rudera'. The un-named ruin group at Puilasoq is marked by a single building. The ice-sheet margin north-east of Puilasoq is marked 'Jökull'. In his description of the locality, Thorhallesen (1914, pp. 46–47) wrote: *At high tide this bay is twice as long, and from a high mountain I saw three or four more rudera [ruins] in the area. The ruins can be seen from a great distance, because the grass, where the field has been fertilised, dies and becomes red in late summer, since it starts growing earlier in the spring. The glacier ice, which covers the uplands from north to south, as far as can be seen, and which covers the highest mountains, falls towards the south-east from Naviangoæt down to the sea, which is perhaps the head of Ujaraksoak fjord, unless it continues farther below the ice. Sometimes large pieces of ice fall down and float around until a strong eastern wind drives them out of the fjord.* (Authors' translation.)

Although the frontal position of Kangilinnguata Sermia is not well defined, it seems that the front during the last half of the 18th century was advancing and that the glacier calved into the fjord, at least at high tide. Hence it is possible that the tidal flat in the inner part of the fjord formed after Thorhallesen's visit.

K.L. Giesecke also visited Ujarassuit Paavat. In his diary, he mentioned on 5–6 August 1808 (Giesecke 1910, pp. 145–147) the earlier visits by H. Egede and E. Thorhallesen, but he only briefly mentions the glacier. Kleinschmidt's map from 1860 (Fig. 11) depicts Ujarassuit Paavat, the bay at Ujarassuit and the head of an outlet from the Inland Ice that almost reaches the inner part of Ujarassuit Paavat. The latter outlet must be Kangilinnguata Sermia. The sketchy contours of the map do not allow us to determine the exact position of the glacier front, but it appears that the glacier did not reach the sea. After a later visit in 1885, by J.A.D. Jensen (Jensen 1889, p. 109), ruin group 8 and its surrounding area were described thus: *Should be located on the north side of Ujaragssuit's north-eastern branch, into which the Inland Ice now protrudes, transporting large amounts of clay that are deposited in the fjord, so that it becomes dry at low tide. Living Greenlanders remember that until around 1840 they could sail up this fjord branch by umiaq to a bird cliff on the south side, but the ice has advanced far beyond this place.* (Authors' translation.)

Based on the statements by Thorhallesen from the middle of the 1700s and those by J.A.D. Jensen from the middle of the 1800s, we suggest that Kangilinnguata Sermia was advancing at this time and that sedimentation in Ujarassuit Paavat was increasing.

Although visited subsequently by D. Bruun in 1903 (Bruun 1917) and by O. Bendixen in 1916 (both mentioned in Bruun 1917, p. 72), no further information was provided about the glacier. Aa. Roussell, after work in 1934, provided detailed descriptions of ruin group 7 (Anavik, now Ujarassuit; Roussell 1941, pp. 32– 34) and group 8 (Puilasoq, pp. 75–77, 167–171). Roussell stated that the distance from ruin group 8 to the front of Kangilinnguata Sermia was around 2 km (Roussell 1941, p. 76). He published a photograph showing the glacier at approximately the same position as at present (Roussell 1941, fig. 52, p. 76).

The glacier was also described by Gripp, who investigated the glacier in 1930 and described marine faunas found in concretions in the moraine and in the alluvial plain in front of the glacier (Gripp 1932). Gripp also described the geomorphology of deposits in front of the glacier and within the glacier, where push and shear moraines occurred (Gripp 1975). Gripp (1932, 1975) published photographs of Kangilinnguata Sermia (Fig. 19A). It appears that the glacier still had no pronounced trimline zone around 1930, but the glacier front was heavily crevassed and partly dominated by shear moraines and about 10 m high push moraines close to the active glacier ice. Gripp's photographs can be compared with aerial photographs of the glacier from 1948, 1968 and 1985 as well as a satellite image from 2007 (Figs 19, 20). Apart from a slight increase in the size of the superficial moraine area in 1948, only small changes are seen in the frontal appearance, in addition to a little thinning.

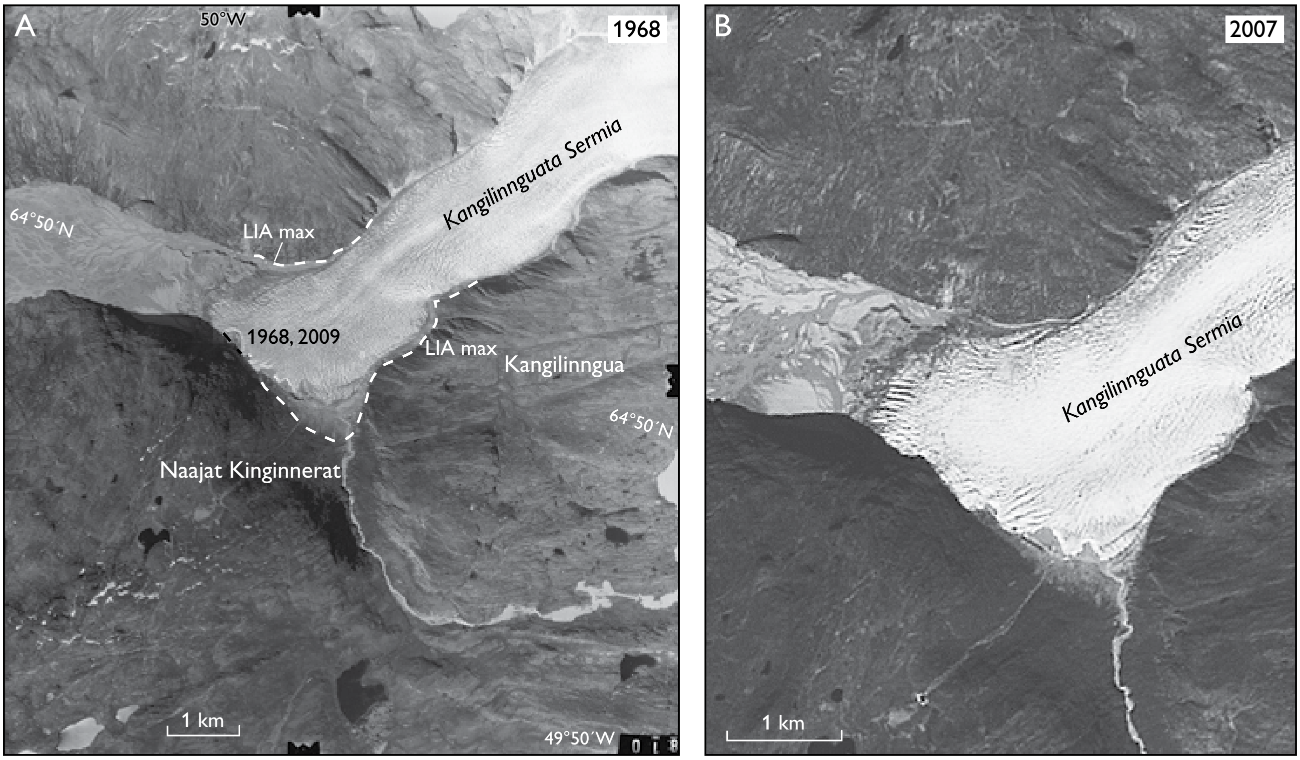


Fig. 20. **A:** Kangilinnguata Sermia on 25 August 1968 (Geodetic Institute, route 281V no. 810). **B:** Kangilinnguata Sermia front on 4 August 2007 (ASTER image). Comparisons between the photographs from 1930 and 1948 (Figs 19A, B), the aerial photograph from 1968 and satellite images from 2007 and 2009 indicate a slight thinning. In addition, a thin trimline zone developed around the glacier front during this 77 year period. **LIA max** (Little Ice Age maximum).

Evaluation

Thorhallesen's description from the 1700s indicates that Kangilinnguata Sermia was calving in the fjord now named Ujarassuit Paavat, but called 'Naviangoæt' by Thorhallesen. It is possible that the interior part of Ujarassuit Paavat was not filled with sediments to such a high degree as at present; if so, Kangilinnguata Sermia may have been a calving glacier even if the front was located at the same place as today. However, it is also possible that calf ice drifted into Ujarassuit Paavat from the Kangersuneq icefjord. From the descriptions from the 1700s and most of the 1800s, it is difficult to determine the position of the glacier front. The records state that the glacier was advancing and possibly at the same time filled the interior parts of the fjord with sediments.

Since only a narrow trimline has developed around the glacier front, its position cannot have been farther west than today during the Little Ice Age (including the narrow belt of shear moraines at the present glacier front). The formation of the proglacial tidal flat can only be explained by increased sedimentation. This is in accordance with the record by J.A.D. Jensen that the head of the fjord could be reached by boat as late as around 1840, but not at the time of his visit in 1885, due to the development of a tidal flat. The formation of this tidal flat can hardly be taken as evidence of a glacier advance, but the notes in J.A.D. Jensen's report on the glacier front passing a bird cliff may provide information about the timing and extent of the advance. Thorhallesen used the name 'Naviangoæt' for the inner part of Ujarassuit Paavat. According to L. Bobé's footnote to Thorhallesen's text (Thorhallesen 1914, p. 46), this place name can be translated as 'Naujanguit', which is used by the Greenlanders for the glaucous gull (*Larus hyperboreus*) and the Iceland gull (*L. glaucoides*); 'Naviangoæt' is thus probably a name for a bird cliff with breeding gulls. The southern side of the frontal parts of Kangilinnguata Sermia borders on a 500–700 m high steep mountain slope, and the mountain is called Naajat Kinginnerat, but no bird cliff is known from the site (D. Boertmann and L.M. Rasmussen, personal communication 2011). However, this could be caused by the present inaccessibility to the place because of the advancing glacier. Confirmation (or the opposite) by local hunters is needed. However, both maps by Kleinschmidt (1860) and Jensen (1889) give the impression that the glacier front in 1885 was still close to its Little Ice Age maximum extent. According to the information presented above, the glacier must have advanced in the first part of the 1800s, after which thinning and development of superficial moraines have occurred throughout the 1900s (Fig. 20).

It is deemed likely, therefore, that J.A.D. Jensen's reference to the advancing glacier passing a bird cliff around 1840 refers to the steep southern mountain slope, today situated 1–2 km behind the Little Ice Age maximum as determined from terminal moraines and a narrow trimline zone. It is suggested that the glacier front passed the bird cliff in the first part of the 1800s during an advance that reached the Little Ice Age maximum extent sometime at or after the middle of that century. The magnitude of the advance may have been between 1 and 2 km (the distance between the cliff and the Little Ice Age maximum extent; Fig. 19).

The first accurate evidence of the position of the glacier front was provided by Gripp after his visit to the glacier in 1930. From his description (Gripp 1932, 1975), the glacier seems to have been surrounded by Little Ice Age moraines and a trimline zone, and it must be concluded that the glacier front was in a stage of initial thinning. The distance from the glacier front to ruin group 8 in 1934 was estimated by Roussell to be 2 km, which is close to the present distance. The Puilassoq ruin site and Kangilinnguata Sermia are shown on a photograph from 1934 by Roussell (Roussell 1941, fig. 52, p. 76).

Aerial photographs from 1936, 1968 (Fig. 20A) and 1985 give the impression that the glacier front was thinning and becoming increasingly covered with surface moraine. The front was probably receding slightly. A Landsat image from 2009 indicates continuous thinning of the front with further development of the trimline zone, but development of dead ice makes it difficult to determine the exact recession of the glacier front. The same is seen on an ASTER image from 2007 (Fig. 20B).

Comparisons with regional glacier fluctuations

The description of the five outlets from the Inland Ice that are found in the Kangersuneq area shows the great diversity in response to past climate changes. In order to discern a possible pattern in the geographical distribution of these responses, it was necessary to look at changes of the outlets from a larger geographical region of the western slope of the Inland Ice. Preliminary investigations of calving glaciers in south-western Greenland were made by Weidick (1994a, b) and of the south-western slope of the ice sheet in general, based on aerial photographs from around 1950 and 1985 (Weidick 1991a, b). It appears that thinning and recession since the Little Ice Age are connected with piedmont-like outlets spreading over extensive lowland areas such as the Qassimiut lobe (Podlech 2004) and Frederikshåb Isblink (described here) in South-West Greenland with relatively small frontal changes, or with large ice streams such as Kangiata Nunaata Sermia and Jakobshavn Isbræ (Sermeq Kujalleq) in West Greenland that show large frontal changes (Fig. 21). Fluctuations of the ice margin are also recorded in other parts of the ice sheet, but the amplitudes are small, and hence it is difficult to identify and date the former changes. However, it appears that a small but widespread advance was characteristic for outlets and marginal parts from around 1950 to 1985. At most localities, the margin only advanced up to a maximum of a few hundred metres during this period. The other outlets from the ice-sheet margin in the Godthåbsfjord region are described below, beginning from the south.

South of Kangersuneq to Frederikshåb Isblink

The outlets in this region are Frederikshåb Isblink, Nakkaasorsuaq in Allumersat fjord (Bjørnesund), Sermeq glacier, Isortuarsuup Sermia, 1CG14004 and Kangaasarsuup Sermia (Fig. 2). Un-named outlets are described using their inventory code numbers according to Weidick *et al.* (1992).