History and exploration

Archaeology

In the Disko Bugt region, the three waves of Palaeo-Eskimo and Neo-Eskimo cultures in West Greenland (Fig. 7) are richly represented by numerous archaeological sites (Larsen & Meldgaard 1958; J. Meldgaard 1983; M. Meldgaard 2004; Gulløv *et al.* 2004). Remains from Palaeo-Eskimo and Neo-Eskimo cultures can be found as far inland as Qajaa, which was situated only a few kilometres from the front of Jakobshavn Isbræ during its maximum extent at around 1850.

The oldest culture, the Saqqaq culture, is dated to the period from *c.* 2500 B.C. to about 800 B.C. At Sermermiut, the deposits of this culture are separated from those of the subsequent Dorset culture by a sterile layer. During the time of the Greenlandic Dorset Culture (also referred to as the Early Dorset culture, *c.* 800 B.C. to 0 B.C.), a smaller and more scattered population lived in the region around Disko Bugt. At about A.D. 1100, the third (Thule) culture arrived in Greenland and settled in the Disko Bugt region about 100 years later (Gulløv *et al.* 2004). The uninhabited periods between the three cultures have been related to climatic deterioration, but other factors such as overexploitation of the natural resources may also have played a role. During some periods, the Disko Bugt region was densely populated, judging from the large number of settlement sites – at least compared to other regions in the Arctic.

The well-known former settlement, the Sermermiut prehistoric 'town' situated close to present-day Ilulissat, was abandoned in the middle of the 1800s. The establishment of the trade centre at Jakobshavn (Ilulissat) by Jakob Severinsen in 1741 was probably the main factor behind the abandonment of Sermermiut.

Although there was certainly some contact between the Thule Neo-Eskimo settlers that migrated from the north and the Norse people that came from the south, the surviving Icelandic sagas provide no identifiable description of the region around Ilulissat.

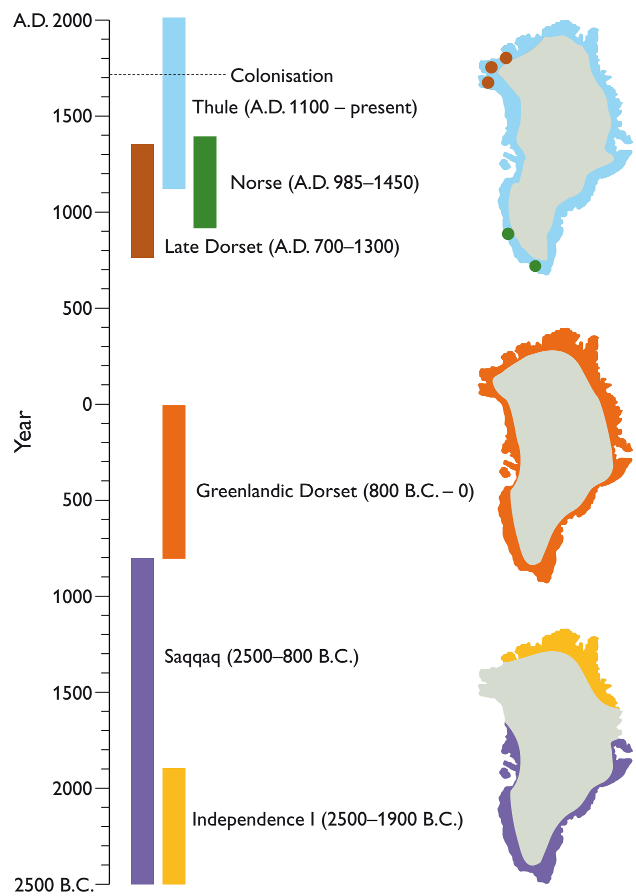

Fig. 7. Chronology of the different archaeological cultures that have colonised Greenland according to Gulløv *et al.* (2004). Modified from Bennike *et al.* (2004).

Discovery, rediscovery, early mapping and descriptions up to c. 1845

The first description of the ice cover of Greenland comes from the Norse people, who settled in southern West Greenland after the arrival of Erik the Red in A.D. 986 (Fig. 7; Gad 1967, p. 43). In 'Kongespejlet' ('The King's Mirror', here cited from the English translation by Larson 1917, p. 143–144), a description written about 1260 records: "In reply to your question whether the land thaws or remains icebound like the sea, I can state definitely that only a small part of the land thaws out, while all the rest remains under the ice. But nobody knows whether the land is large or small, because all the mountain ranges and all the valleys are covered with ice, and no opening has been found anywhere". Although this description concerns southern Greenland, it is generally valid for the whole of Greenland.

The Norse settlements were abandoned in the 1400s (Gad 1967; Arneborg 1996). The disappearance of the Norse population is often linked with the onset of the Little Ice Age although other factors, such as exhaustion of natural resources, rising sea level, the political situation in

Facsimile von Paul Egede's Karte von Grönland 1788.

Fig. 8. Poul Egede's map of Greenland from 1788, showing the fictitious strait extending across Greenland from Disko Bugt to the coast of East Greenland (from Nordenskiöld 1886, p. 212). The size of the original map is 294 × 379 mm.

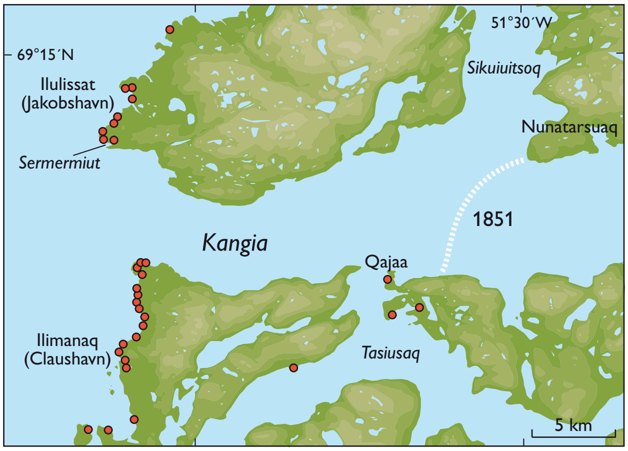

Fig. 9. Map of Kangia and the surrounding region, showing the location of former Inuit settlements (indicated by the red dots) and the approximate position of the front of Jakobshavn Isbræ (Sermeq Kujalleq) in A.D. 1851 (white line). Compiled by the National Museum and Archives of Greenland; modified from Bennike *et al.* (2004).

Scandinavia, the black death (plague), or attacks by Eskimos or Biscay pirates, may also have played a role (Gad 1967).

Apart from sporadic observations by English and Dutch whalers and explorers, there are no descriptions of the physiography of Greenland or its ice cover during the 1500s and 1600s. For Disko Bugt in particular, the survival of numerous place names of Dutch origin (Rodebay, Claushavn, Vaigat etc.) is linked to Dutch whaling activity in the 1600s and the beginning of the 1700s. An early description of the icefjord was published by the Dutch whaler, Feykes Haan, in a navigation guide: "Half a mile north of Sant-Bay is a fjord that is always full of ice, with frightfully tall icebergs, but from where they come is unknown. This fjord is called Ys-Fioert [Icefjord]." (Haan 1719, quoted from Bobé 1916, p. 47; authors' translation). Short as it is, this description reveals that the conditions of the iceberg bank and the icefjord in the early 1700s were much the same as can be seen today.

Up to the beginning of the 1700s, knowledge of the West Greenland coastal region was poor. In 1721, however, the priest Hans Egede settled in Greenland near Godthåb (now Nuuk, at *c.* 64°10´N), and in subsequent years permanent trading stations and missions spread rapidly. By the end of the 1700s, a network of Danish settlements covered West Greenland from Nanortalik in the south (at 60°N, established 1797) to Upernavik in the north (at 72°N, established 1772). In the Disko Bugt region, Qasigiannguit (Christianshåb) was established in 1734, Ilulissat (Jakobshavn) in 1741, Aasiaat (Egedesminde) in 1763 and Qeqertarsuaq (Godhavn) in 1773.

With colonisation came the first attempts to undertake a systematic mapping of Greenland (in particular West Greenland) and also an increasing number of local descriptions were made. The development of early mapping is described and illustrated by Dupont (2000). Poul Egede's map from 1788 illustrates the status of mapping at that time (Fig. 8). Apart from the lack of detail, it should be noted that a channel is depicted connecting Disko Bugt in West Greenland with Kangerlussuaq in East Greenland. This so-called 'Frobisher Strait' is an error copied from older maps. Egede commented on the map: "It is said that the strong current that flows continuously from the ice-dome comes from Ollum Længri Fjord" (i.e. from East Greenland; authors' translation). Egede also stated in another comment to the map: "The entire land is concealed under ice and snow, from Staten Huk to the extreme north" (authors' translation). 'Staten Huk' was the Dutch whalers' name for Kap Farvel at the southern tip of Greenland. The way this is expressed perhaps indicates some doubt about the alleged channel through Greenland. Egede's comments about the icefjord, with respect to the strong currents from the glacier may be based on observation, as may his depiction of the icefjord with a length similar to the present.

Historical descriptions of the conditions in Kangia and its surroundings were collated by Larsen & Meldgaard (1958), supplemented by Georgi (1960a, b). Both stressed the records that the icefjord was more ice-free in the early 1700s than in subsequent times. This conclusion is essentially based on a letter from the manager of Jakobshavn, Hans Rosing, from 1831. It states in translation: "An old woman still living here [at Jakobshavn] knew, when she was young, another old woman who told her that, when she was a young girl, there were practically no icebergs in the fjord, but the water was so open that the Dutchmen with their large vessels went into the fjord. Up along the coast of the fjord the Greenlanders lived in their tents, and in the winter there were houses of which ruins still can be seen at least one 'miil' [approx. 10 km] from the mouth" (Larsen & Meldgaard 1958, p. 24–25). Historically these events can be related to a time just before 1740. This evidence can be combined with descriptions from a visit to the ice margin on 16 January 1747 by P.O. Walløe (Bobé 1927). Walløe described the advancing ice margin in so much detail that there can be little doubt of the validity of his observations, which were probably made close to Qajaa (Fig. 9). Qajaa was abandoned in the middle of the 1700s, presumably because of the advance of Jakobshavn Isbræ in the 18th and first half of the 19th century. Rink (1875, p. 15) provides further confirmation: "…proof that Jakobshavn-Fjorden was earlier accessible further in, is given by the remains of an older dwelling site in a location that can-

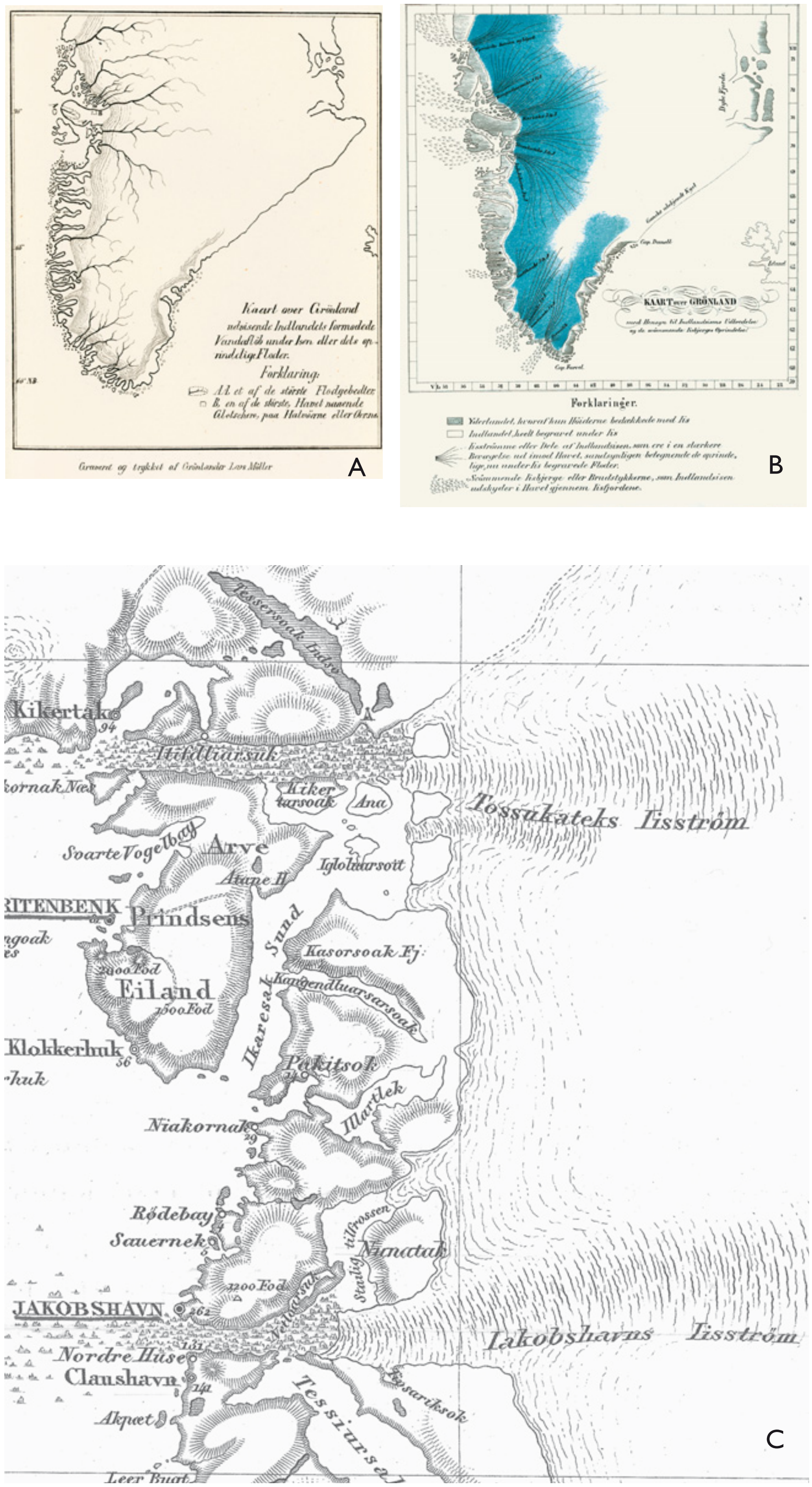

Fig. 10. **A**: Rink's concept of the drainage of the interior of Greenland by rivers (Rink 1862). The outline of East Greenland was then not well known, and the depiction of the area north of Ilulissat in West Greenland is also imprecise. **B**: Rink's map showing the extent of the Inland Ice, and the large ice streams that drain into Disko Bugt and Uummannaq Fjord (Rink 1857). Smaller glaciers in southern Greenland are also indicated. **C**: Segment of Rink's original map of the interior part of Disko Bugt showing the positions of the ice streams draining into Kangia and Torsukattak (Rink 1853).

not be reached now due to ice" (authors' translation). Together these observations lead to the conclusion that the glacier could have been in a rather retracted position in 1747, but perhaps in an initial advancing state. The glacier may well have been just as productive then as it is now, as implied by Haan's description of icebergs on the iceberg bank in 1719. An initial advance in the beginning of the 1700s may only have led to a slight reduction in calf-ice production.

Unfortunately, the observations on the advancing ice margin around Jakobshavn Isbræ up to *c.* 1850, backed up by records of vegetated soil or ruins buried by the advancing ice, generally lack information as to the exact location at which they were made.

These observations from the 18th and the beginning of the 19th century, however, form valuable contributions to the growing interest in the changes of ice cover. The observations on the Greenland ice cover from the 18th century were compared by Cranz (1770) with the status of European and American glaciers, which were then also advancing. This provided impetus for more detailed mapping and descriptions of the Greenland ice cover in the following century, when it was first appreciated that glaciers could be regarded as a kind of 'climatoscope', with their recessions and advances reflecting alternating warm and cold periods. In Greenland, systematic observations and descriptions of the ice cover were initiated by Hinrich Johannes Rink and recorded in a series of outstanding publications.

Hinrich Johannes Rink (1819–1893)

Originally educated in chemistry and physics (Oldendow 1955), H.J. Rink carried out geological investigations in parts of northern West Greenland between 1848 and 1852. From 1853 to 1858 he was trade manager in Qaqortoq (Julianehåb) and Nuuk (Godthåb), and from 1858 to 1868 he was inspector of the Royal Greenland Trade in South Greenland. He travelled over large parts of West Greenland. One of his ambitions was to produce a pioneer map of West Greenland, incorporating his own mapping with that of older sea charts, the mapping of the missionary Samuel Kleinschmidt (1814–1886; see Wilhjelm 2001, p. 144–152), and map sketches made by local hunters. He devoted much of his own mapping efforts to the interior, eastern ice-free fjords and land areas that were largely unknown at the time. During his travels he visited, described and mapped extensive areas of the icefjords and their glaciers. Rink stayed in Ilulissat (Jakobshavn) over the winter of 1850–1851, and sailed to the Inland Ice margin at the fjord Paakitsoq, north of Ilulissat, in October 1850. He also travelled by dog sledge to the southern side of the front of Jakobshavn Isbræ in April 1851 (Rink 1857; vol. 1) and visited the north side of the glacier in May the same year (von Drygalski 1897, p. 129). His approximate determination of the frontal position of Jakobshavn Isbræ is shown in Fig. 9, as depicted in later reviews. The original version of Rink's map is shown in Fig. 10.

Rink's observations of the frontal position of Jakobshavn Isbræ in 1850–51 were the first in a series of observations that have now extended over more than 150 years. The long series of observations of the frontal changes and the velocity of Jakobshavn Isbræ (from 1875), and the long series of continuous meteorological records at Ilulissat (since 1873), are unique for an Arctic area.

Rink was the first scientist to appreciate the immense extent and special form of the 'ice plain', covering the entire interior region of Greenland. Rink called it 'Indlandsisen' [the Inland Ice] following a suggestion by the Danish scientist Japetus Steenstrup. It was clear to Rink that this large body of ice was quite different from the local glaciers hitherto described from other parts of the world. In Europe a new idea was emerging at this time, namely that extensive ice sheets had covered large parts of northern Europe in the past. Rink's demonstration of an extant, immense ice sheet in Greenland was sensational news, and provided critical support for arguments that such an ice cover had once existed in Europe. While it is true that earlier mapping and descriptions, such as Poul Egede's map (Fig. 8), had indicated the presence of extensive ice in Greenland, it was Rink's detailed observations and descriptions that provided documentary evidence, and provided the basic background for the numerous subsequent glaciological investigations in Greenland.

In his attempts to understand the origin and dynamics of the Inland Ice, Rink also ventured into many of the problems that concern the mechanics of calf-ice production. Rink's main thesis was that just as precipitation over land areas is drained by rivers, the ice streams deriving from the interior of Greenland drain the snow and ice. Ice streams act as 'rivers' in a surrounding area of 'quiet', dynamically less active ice (Fig. 10; Rink 1862).

Rink estimated the production of calf ice on the basis of glacier size and the quantity of ice in the fjords. On these criteria, Rink (1857, 1862) recognised five ice streams ('isstrømme') of 'the first order', namely Jakobshavn (69°10′N), Tossukatek (69°5′N), Den større Kariak (70°25′N), Den større Kangerdlursoak (71°25′N) and Upernivik (73°N; Fig. 10); the spelling used by Rink is retained here. Rink estimated the catchment area for each of the five ice streams to be at least *c.* 50 000 km^2 (*c.* 1000 Danish square miles) (Rink 1875, p. 15), a clear indica-

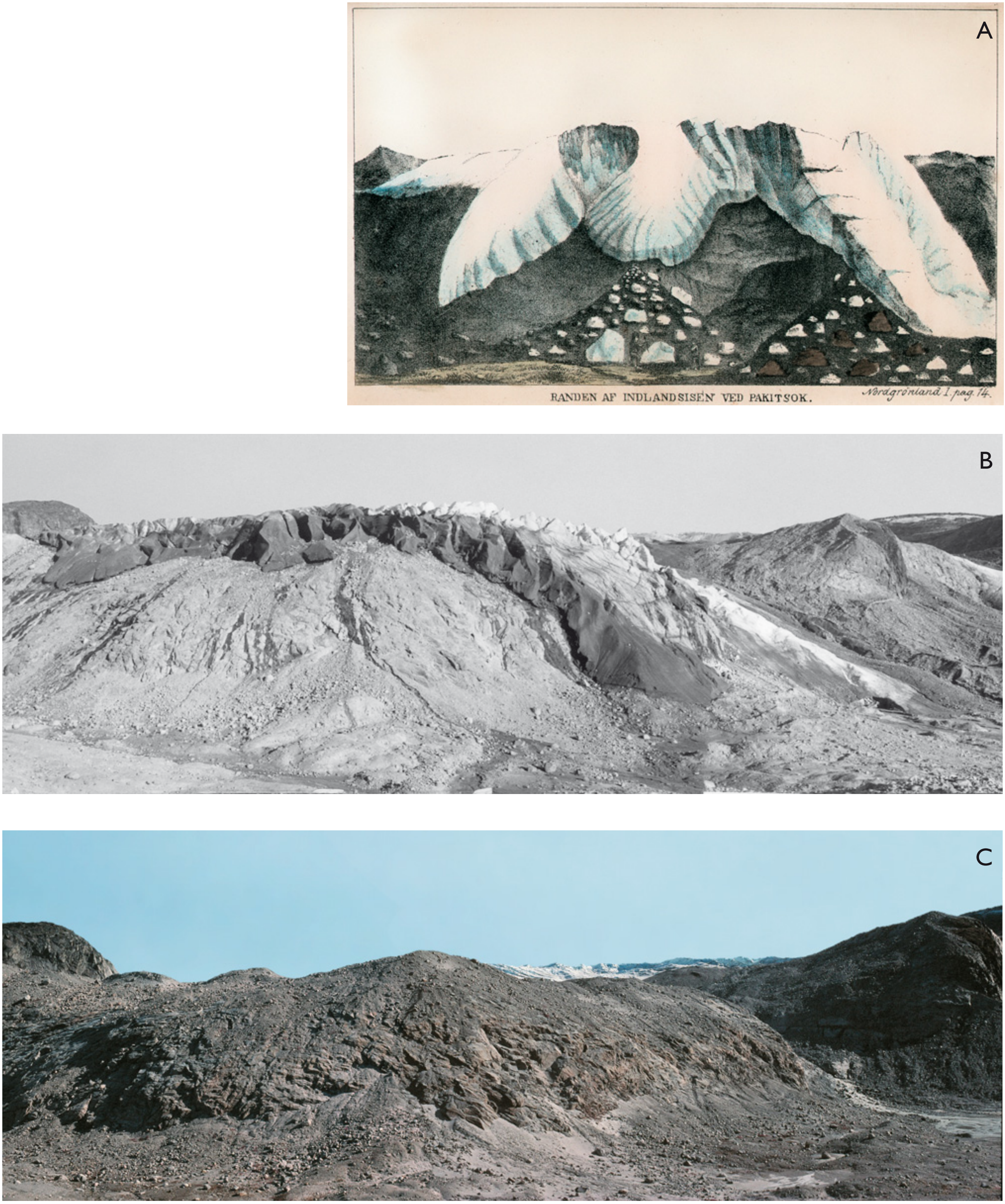

Fig. 11. The margin of the Inland Ice at Paakitsoq north of Kangia; the central hill is about 80 m high. The three images (**A**: lithograph, H.J. Rink, 1850. **B**: photograph, A. Weidick, 1961. **C**: photograph, H.H. Thomsen, 1987) illustrate changes in the ice margin at this site. In 1850, the glacier front was advancing, reaching a maximum around 1880. Since then a gradual thinning has taken place as can be seen from the photographs from 1961 and 1987.

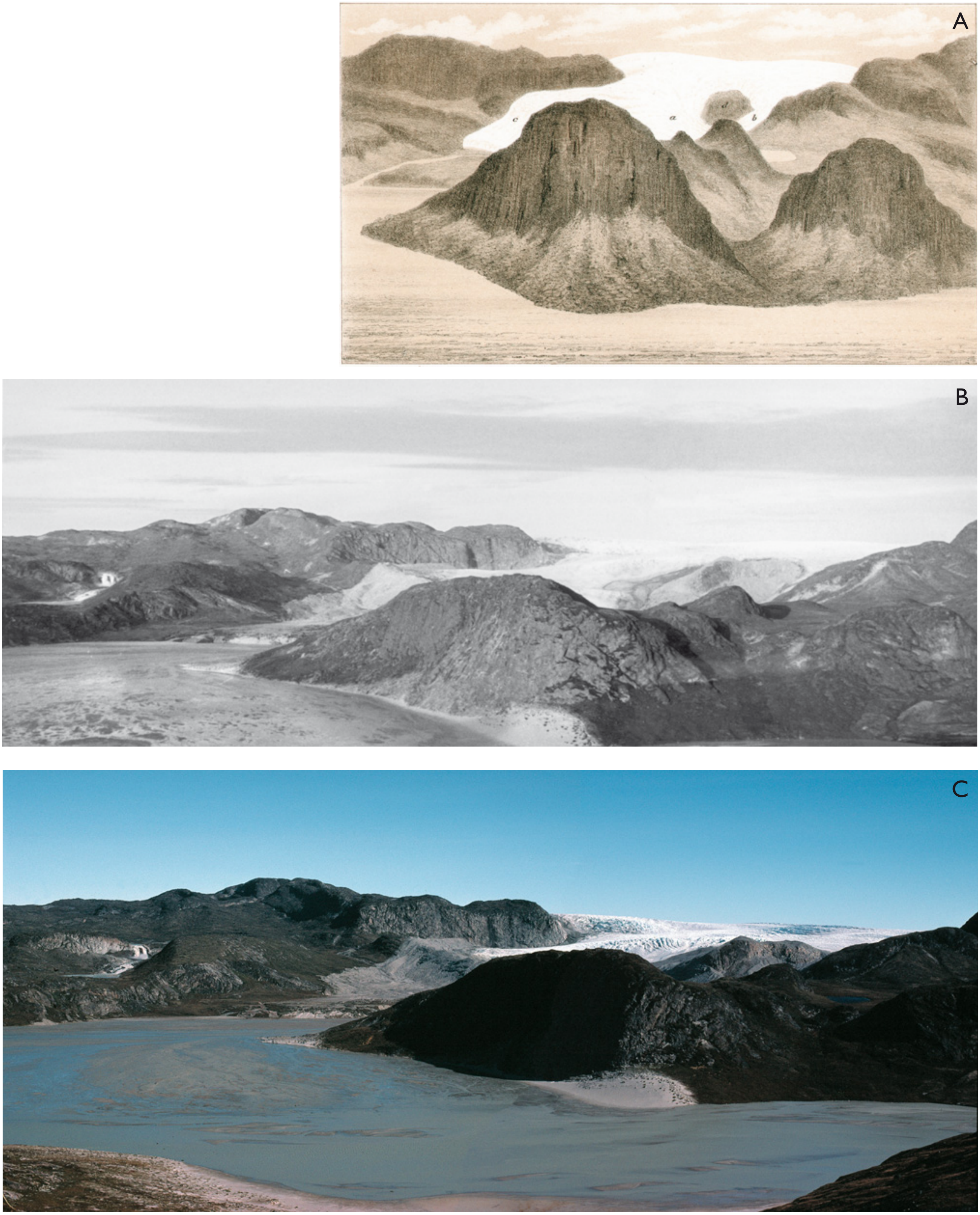

Fig. 12. The lobe of the Inland Ice margin at Paakitsoq, seen from the south-west; the central hilltop is about 150 m high. **A**: R.R. Hammer's drawing from 1883, which marks the maximum historical extent of the glacier lobe. The photographs from 1961 (**B**: A. Weidick) and 1987 (**C**: H.H. Thomsen) illustrate the progressive thinning of the ice margin.

tion that he recognised the extraordinary size of the Greenland ice sheet. However, while recognising the large calf-ice production from these major outlets, Rink did not appreciate the unique status of Jakobshavn Isbræ at Ilulissat. This was first recognised in the second half of the 19th century, during investigations on the rate of movement. Several illustrations in Rink's papers provide details of the extent of the glacier cover in the middle of the 1800s, of which Figs 11 and 12 are examples showing Paakitsoq, north of Ilulissat.

Observations and mapping of the ice margin around Disko Bugt

As mentioned above, interest in Greenland glaciers increased during the second half of the 19th century. An increasing number of scientists visited the ice margin around Disko Bugt, and most of these provided descriptions of the front or the Inland Ice margin around Jakobshavn Isbræ. A chronological list of the most significant visits after Rink is given below.

1867. The British mountaineer Edward Whymper made a visit to the area around Qajaa in Kangia. He noted that the glacier ice was too crevassed to allow passage to the Inland Ice (Whymper 1873; Nordenskiöld 1886, p. 121).

1870. A.E. Nordenskiöld visited West Greenland, and described the icefjord and the front of Jakobshavn Isbræ. He could not determine the boundary between the front of the glacier and the calf ice in the fjord (Nordenskiöld 1871; Engell 1904). His visit to Jakobshavn Isbræ was undertaken in connection with one of the early attempts to visit the interior of Greenland, and Nordenskiöld also visited Nordenskiöld Gletscher (Akuliarutsip Sermerssua), *c.* 90 km south of Jakobshavn Isbræ. Here, from the head of Arfersiorfik fjord, he led a reconnaissance expedition that reached 56 km into the ice sheet at an altitude of 670 m a.s.l. In 1883, from the same starting point, another party led by Nordenskiöld reached *c.* 350 km into the Inland Ice to an altitude of 1947 m. Surface features of the ice, such as cryoconite holes (meltholes) and glacier spouts, were described.

1875. A. Helland visited Jakobshavn Isbræ in July 1875 and conducted the first measurements of the rate of movement, which were published together with a description of the position of the front of Jakobshavn Isbræ (Helland 1876). He also measured the movement of Sermeq Avannarleq in Torsukattak icefjord, *c.* 100 km north of Jakobshavn Isbræ, and described the surface of the ice margin at Paakitsoq.

1879. K.J.V. Steenstrup (1883a) also visited Sermeq Avannarleq in Torsukattak icefjord, and measured the rate of movement of this glacier in May 1879 and 1880.

1879. R.R.J. Hammer mapped the entire fjord system around Kangia, including the glaciers at the heads of the tributaries of Sikuiuitsoq and Tasiusaq (Hammer 1883). Hammer also determined the position of the front of Jakobshavn Isbræ in September 1879.

1880. R.R.J. Hammer repeated his visit to Jakobshavn Isbræ in March and August 1880. A winter advance of *c.* 1 km and a subsequent summer recession of *c.* 2 km were recorded. The rate of movement was determined from the southern edge of the glacier front to its central part. Hammer found that the movement was not uniform, and could find no relationship between air temperature and glacier velocity. The position of the front was observed to be very variable, and Hammer concluded that large icebergs were released by fracturing of the ice front due to the buoyancy of the floating part of the glacier. Hammer also tried to evaluate the hydrographic conditions of the icefjord.

1883. R.R.J. Hammer mapped the eastern parts of Disko Bugt between *c.* 68°30′ and 70°N (Hammer 1889), and made a sketch of Jakobshavn Isbræ while attempting to determine the glacier recession since 1851.

1883. A.E. Nordenskiöld revisited Nordenskiöld Gletscher (see 1870 above).

1886. Robert E. Peary made an attempt to reach the interior of the Inland Ice from a starting point at Paakitsoq, 40 km north of Kangia. Accompanied by C. Majgaard he reached a point *c.* 185 km into the ice sheet at an altitude of almost 2300 m a.s.l. Peary also described the landscape of the ice margin (Peary 1898).

1888. S. Hansen made a sketch map of the front of Jakobshavn Isbræ for the Royal Danish Sea Chart Archive (Engell 1904). According to Engell, a photograph from this visit showed the frontal position of Jakobshavn Isbræ to lie farther to the east than indicated on Hansen's 1888 map.

1891. In June 1891 the German polar explorer Erich von Drygalski visited the north side of Kangia.

1893. von Drygalski visited the area to the south of the front of Jakobshavn Isbræ in February 1893, and plotted the frontal position on a map, although it was difficult to determine the position precisely (von Drygalski 1897).

1902. M.C. Engell measured the frontal position of Jakobshavn Isbræ in July 1902, and showed that the recession had continued (Fig. 13). Velocity determinations were similar to those previously measured (Helland 1876; Hammer 1883; Engell 1904). In addition, Engell made an extensive description of the whole fjord region, and produced detailed maps of the front of Jakobshavn Isbræ and the ice margin at the head of Orpissooq fjord in the south-eastern corner of Disko Bugt.

1903. M.C. Engell again visited Jakobshavn Isbræ in July 1903, but could only determine the frontal position with some uncertainty; it appeared to be *c*. 350 m farther west than in 1902. Engell observed the release of a large iceberg (Engell 1910).

1904. M.C. Engell made his third visit to the front of Jakobshavn Isbræ in the summer of 1904 although, the position of the glacier front was not determined (Engell 1910). He mapped the interior of Disko Bugt from *c*. 68º 45´N (head of Tasiusaq fjord) to *c*. 70º 05´N (Torsukattak icefjord).

1912. Alfred de Quervain and Paul-Louis Mercanton made a west-to-east crossing of the Inland Ice from Eqip Sermia in Disko Bugt to Ammasalik in East Greenland. A description of the ice margin around Eqip Sermia, *c*. 70 km north of Ilulissat, was later published (de Quervain & Mercanton 1925).

1913. Johan P. Koch and Alfred Wegener made an east-to-west crossing of the Inland Ice during their 1912–1913 expedition. In August 1913 the two scientists visited Jakobshavn Isbræ, and their determination of the frontal position indicated a significant recession since 1902 (Koch & Wegener 1930).

1929. During the 1929 preparations for the German Alfred Wegener Expedition to the Inland Ice in 1930–1931, reconnaissance for an alternative route to the ice sheet was made in Disko Bugt. During May and June, the equipment was tested and ablation measured on a route that extended 150 km from Eqip Sermia north-eastwards into the Inland Ice reaching an altitude of 2090 m. Jakobshavn Isbræ was visited in September 1929, and the front position and the velocity determined. The frontal positions of Eqip Sermia and the glaciers in Torsukattak icefjord were also described (Georgi 1930; Wegener *et al.* 1930).

1931/32. The position of the glacier front of Jakobshavn Isbræ was depicted on the first 1:250 000 scale map sheet of the Jakobshavn area, issued by the Geodetic Institute, Copenhagen.

1934. Martin Lindsay started a traverse of the Inland Ice from Eqip Sermia, from the same starting point that de Quervain and Mercanton used in 1912. The main objective of the three-man expedition was to explore the mountainous region south-west of Scoresby Sund in East Greenland (Fristrup 1966).

1936. Eigil Knuth and Paul-Emile Victor participated in a French/Swiss/Danish expedition that crossed the Inland Ice from the ice margin *c*. 80 km south of Ilulissat to Ammasalik in East Greenland. A description of the ice-margin landscape was published by Knuth (1937).

After 1936. During and after the World War II, there were rapid developments in aerial photography techniques. The increase of information can be illustrated by the archive of aerial photographs of the region available at the National Survey and Cadastre in Copenhagen, dating from the years 1942, l946, 1948, 1953, 1957, 1958, 1959, 1964 and 1985.

Large-scale glaciological projects after World War II

After World War II, a series of major investigations of the Inland Ice was carried out by military and scientific organisations. A detailed account of this work is outside the scope of this bulletin, and the investigations are only briefly mentioned here as a background for the research around Disko Bugt itself. Reviews of the history of exploration of the Greenland ice sheet and the significant results achieved are given by Fristrup (1966), Reeh (1989) and Dansgaard (2004).

The new era of scientific expeditions was initiated by the Expéditions Polaires Francaises (EPF 1948–1953), which continued the work of the German Alfred Wegener Expedition of 1929–1931. EPF worked along an east–west profile from coast to coast over the central part of Greenland, and in addition to geodetic and geophysical work carried out mass-balance measurements along the route. Detailed mapping of the ice sheet margin and descriptions of the area around Eqip Sermia were also made.

The successor of EPF was the Expédition Glaciologique Internationale au Groenlande (EGIG 1957–1960), an international collaboration between Austria, Denmark, France, Germany and Switzerland. EGIG included in its programme a project that aimed at photogrammetric determinations of the rate of movement and estimates of calf-ice production of all outlets from the Inland Ice that drain into Disko Bugt and the Uummannaq Fjord. Vertical aerial photographs were used for this work. In 1957, flights were repeated at intervals of four to five days (Bauer *et al.* 1968a), and in 1964 for the same glaciers at intervals of about two weeks (Carbonell & Bauer 1968). The project confirmed the paramount role of Jakobshavn Isbræ with respect to calf-ice production, compared to other productive glaciers in Greenland (Fig. 5). Variations in the frontal position of Jakobshavn Isbræ were also determined (Fig. 13).

The EGIG work continued after 1960 with follow-up projects. One important task was to determine the thickness of the Inland Ice, and hence also the elevation and topography of the landscape below the ice, by means of airborne radar. Prior to this initiative, the thickness had only been measured along a few profiles traversing the Inland Ice (Holtzscherer & Bauer 1954), using seismic, gravimetry or radar techniques. The Technical University of Denmark (DTU) in collaboration with the US National Science Foundation and the Scott Polar Research Institute in England modified the radar technique for use in aircraft. During six seasons between 1968 and 1976, more than 60 000 km of profiles were flown, and for the first time a large-scale map of the landscape under the Inland Ice became available (Gudmandsen & Jakobsen 1976). At that time, this subsurface map was a major breakthrough with significant implications for the understanding of ice dynamics, Quaternary geology and geomorphology. However, details such as the continuation of the deep fjords under the present Inland Ice margin could not be resolved, because radar waves could not penetrate the chaotic, crevassed ice of the ice streams. This problem was solved at Jakobshavn Isbræ by applying seismic methods (Clarke & Echelmeyer 1996).

American military groups developed ways of travelling on the ice sheet, erected and maintained Inland Ice stations, and were also directly involved in scientific operations. The latter included the first deep drilling through the ice sheet at Camp Century in 1963–1966 (Langway 1970; Langway *et al.* 1985). The first systematic mapping of snow accumulation over the entire Inland Ice was carried out by Cold Regions Research and Engineering Laboratory, Corps of Engineers, US Army (CRREL) in 1952–1955 and 1959–1960, and led to a division of the Inland Ice surface into dry snow, percolation facies and wet-snow facies according to altitude (Benson 1959, 1962, 1994, 1996; Ragle & Davis 1962). More recently, the National Aeronautics and Space Administration (NASA) has been responsible for the development and maintenance of the present satellite and airborne monitoring system (Sohn *et al.* 1997a; Williams & Hall 1998; Thomas *et al.* 2001). This system provides detailed information on current changes of surface elevation, volume and rate of movement of the Greenland ice sheet.

The development of the global positioning system (GPS) and airborne and satellite-based altimetry has resulted in a vast expansion of data. The main focus has been on assessing the impact of climate change on the mass balance of the ice cover, especially with respect to volume changes and surface movements of the major outlets of the ice sheet (Garvin & Williams 1993). In 1994, NASA conceived a

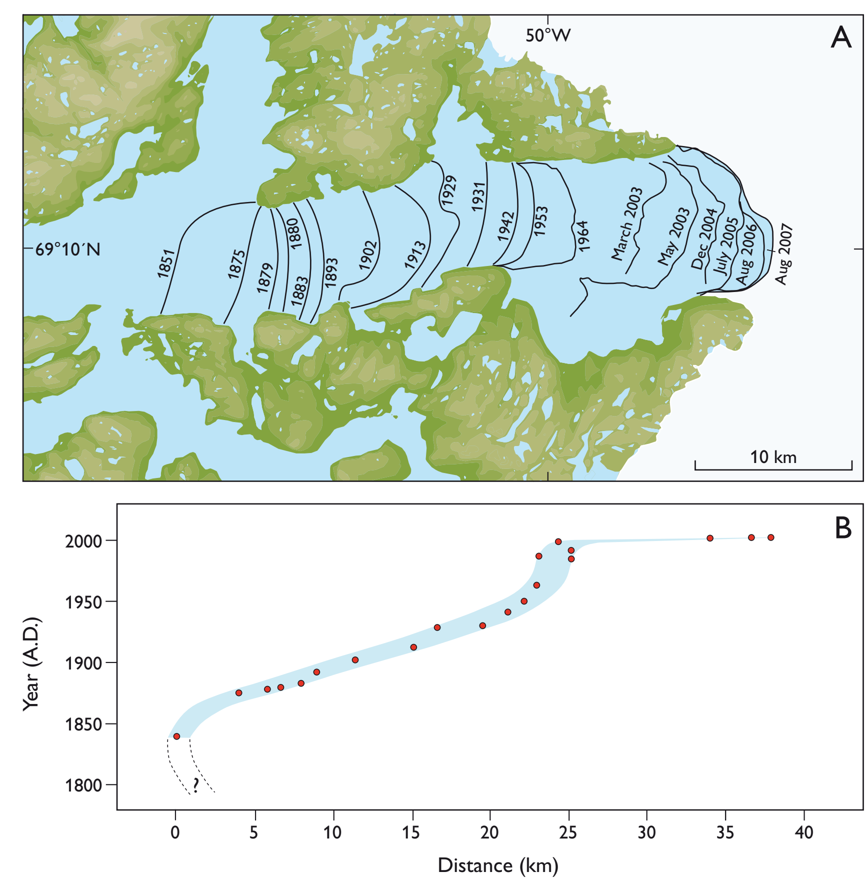

Fig. 13. **A**: Frontal positions of Jakobshavn Isbræ from 1850 to the present. Modified from Bauer *et al.* (1968a) and Weidick *et al.* (2004a). **B**: Recessional curve of the Jakobshavn Isbræ glacier front, up to 1964 based on the positions given by Bauer *et al.* (1968a). The younger parts of the curve are based on satellite information by Stove *et al.* (1983), Sohn *et al.* (1997a, b), later Landsat, ASTER and MODIS images (Alley *et al.* 2005; Cindy Starr, NASA (personal communication, 2007)) and data from a reconnaissance in 2005 (F. Nielsen, personal communication 2006). The width of the curve depicts the range of seasonal variations in the positions of the glacier front. Note the rapid break-up and recession from 2002.

Program for Arctic Regional Assessment (PARCA), which for a decade has collected mass balance data covering the entire ice sheet, with a back-up of 'ground-truth' stations (Abdalati 2001; Abdalati *et al*. 2001). The programme includes the collection of ice-thickness data around Jakobshavn Isbræ (Gogineni *et al*. 2001), where one of the 'ground-truth' stations is located. This is the 'Swiss Station' established at the equilibrium line near Jakobshavn Isbræ by the Eidgenössische Technische Hochschule Zürich, Switzerland (ETH), and later operated by the University of Colorado (Steffen & Box 2001; Zwally *et al*. 2002).

With respect to subsurface mapping around Jakobshavn Isbræ, some details were added during investigations of the hydropower potential for the towns of Ilulissat and Qasigiannguit 1982–1992 (Thomsen *et al*. 1989; Braithwaite 1993). These investigations collected data for the 'quiet' parts of the Inland Ice margin (the areas between the ice streams), using a radar device carried by helicopters. The device was developed by DTU and modified by the Geological Survey of Greenland (Thorning *et al*. 1986; Thorning & Hansen 1987). The most recent radar thickness measurements of the ice sheet (with particularly detailed coverage around Jakobshavn Isbræ) were published by Bamber *et al*. (2001), Gogineni *et al*. (2001) and Layberry & Bamber (2001).

Deep cores from the ice sheet

The constant deposition of snow over the interior parts of the ice sheet results in the compaction of the underlying snow and conversion to glacier ice, which in the course of time flows downwards and outwards towards the margins of the Inland Ice. The discovery of the capability of the ice to preserve information about the climate at the time of snow deposition has given remarkable results with respect to climate change and related geological and atmospheric changes. A number of intermediate and deep ice cores have been recovered from the Greenland ice sheet (Reeh 1989). Of the five deep cores (Fig. 3), the first was made at Camp Century (77°11´N, 61°08´W) in 1964–1966, and had a length of 1390 m (Dansgaard *et al*. 1969; Langway 1970; Langway *et al*. 1985; Reeh 1989). Subsequently, a 2037 m long core was retrieved at Dye 3, where drilling was completed in 1981 (65°11´N, 43°49´W; Langway *et al*. 1985; Reeh 1989). The success of these cores was followed up by two >3000 m deep cores at Summit, on the highest point of the ice sheet, namely the GRIP core (72°34´N, 37°37´W; Johnsen *et al*. 1997) and the GISP2 core (72°35´N, 38°29´W; Grootes *et al*. 1993). The fifth deep core was completed at the NorthGRIP site (75°06´N, 42°19´W) in 2001, and reached a depth of 3001 m (Dahl-Jensen *et al*. 2002). All cores have provided detailed climatic information about the last ice age, and the cores from the central parts of the Inland Ice provide information on the climate up to *c*. 250 000 years back in time.

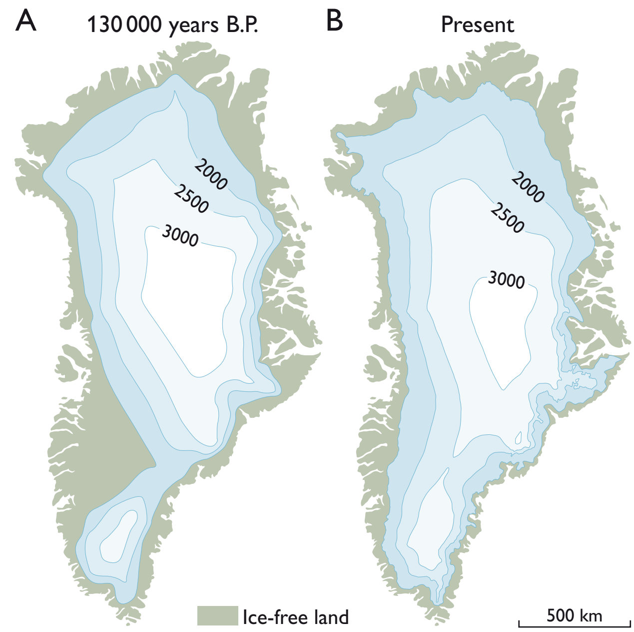

Fig. 14. **A**: Model of the surface elevation of the Greenland ice sheet during the last interglacial (Sangamonian/Eemian) according to Letréguilly *et al*. (1991a, b). **B**: Modern-day surface elevation according to Escher & Pulvertaft (1995).

The data obtained from the ice cores, together with detailed information about the subsurface and surface of the ice sheet, have been incorporated into models of changes of the ice sheet with time, as well as scenarios for the future development of the Inland Ice (Fig. 14; Letréguilly *et al*. 1991a, b; Weis *et al*. 1996; Ritz *et al*. 1997; Huybrechts 2002; Alley *et al*. 2005).

Hydropower and climatic change

The energy crisis in 1973 led to a focus in Greenland on the utilisation of local energy sources, as an alternative to imported oil. In Greenland, hydropower was the obvious potential source of power, but an evaluation required systematic collection of hydrological and glaciological data. As part of a project carried out by the Geological Survey of Greenland (GGU), a series of stations was erected along the Inland Ice margin in West Greenland between *c*. 60° and *c*. 70°N. Data were collected for a hydropower project to serve the town of Ilulissat, and also a project 45 km further south to serve the town of Qasigiannguit. The aim

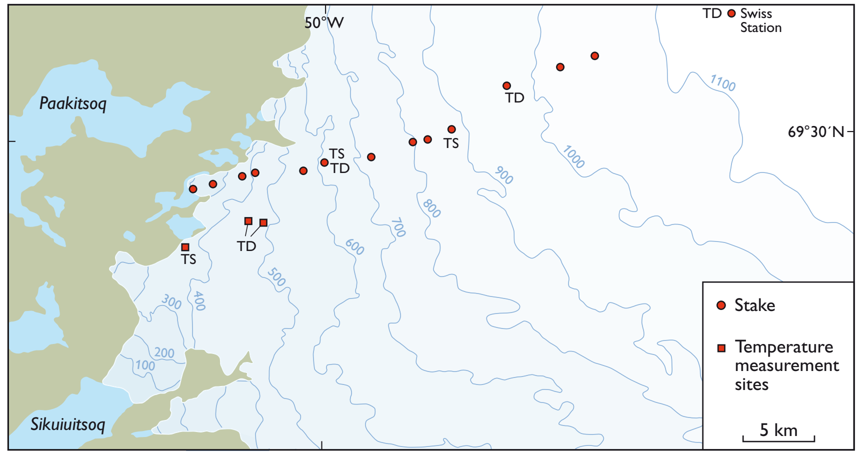

Fig. 15. The drainage basin at Paakitsoq, north of Ilulissat, where the Sermeq Avannarleq glacier enters Sikuiuitsoq (Fig. 2), showing the positions of stakes used for mass balance calculations. **TS** and **TD** mark the positions of shallow and deep thermistor-strings, respectively, that were used for measuring temperatures in the ice. The Swiss Station marks the highest point of the glacier hydrological survey. From Thomsen *et al.* (1991).

of both projects was to determine the amount of meltwater runoff from the ice-sheet margin.

The northernmost station at Paakitsoq, *c.* 40 km north-east of Ilulissat, was started in 1982 (Thomsen *et al.* 1988; Olesen 1989). The studies covered mass-balance measurements along a line of stakes extending from the ice-sheet margin at *c.* 230 m a.s.l. to *c.* 1050 m, close to the equilibrium line (Fig. 15). The studies included drilling of ice holes for measuring ice temperatures and subglacial melt. A detailed map of the subsurface of the ice margin around Jakobshavn Isbræ was also produced (Thomsen *et al.* 1988; Olesen 1989; Weidick 1990).

The data collected from Paakitsoq have not yet resulted in a decision to exploit hydropower for Ilulissat. The annual potential is around 72 GWh for Ilulissat and *c.* 11 GWh for Qasigiannguit (Nukissiorfiit 1995). However, a hydropower plant is now in operation near Nuuk in West Greenland (Kangerluarsunnguaq power plant, production 185 GWh/year), and two other power plants at Qaqortoq/Narsaq in South Greenland and at Ammassalik in South-East Greenland have been established.

The debate on climatic change due to the increasing greenhouse effect and the increased melting of glaciers has stressed the need for data on the actual melting at the ice margin of the Inland Ice. The mass-balance measurements by GGU that started in 1982 in relation to hydropower, were therefore continued in 1990 in collaboration with teams from the Alfred Wegener Institute for Polar and Marine Research, Germany (AWI) and ETH (Thomsen *et al.* 1991). Energy-balance measurements at the equilibrium line were made from a permanent field station on the ice, and a programme for ice-temperature measurements was also set up in a collaboration between GGU and ETH. The original stake line measured from 1982 was extended from 1100 to 1600 m a.s.l. The ETH programme to study climate, energy balance and the thermal regime covered the years 1990 and 1991 (Ohmura *et al.* 1991), with participants from the Institute of Arctic and Alpine Research (INSTAAR, University of Colorado, Boulder, USA). INSTAAR runs a long-term project that aims to investigate the effects of refreezing of meltwater runoff from the Inland Ice, by studies of snow and ice hydrology, heat transfer, and using modelling (Pfeffer *et al.* 1991).

Satellite and airborne radar and laser altimetry with large-scale coverage is now an important tool for monitoring changes in the geometry and dynamics of the ice sheet (Garvin & Williams 1993; Thomas *et al.* 2001). However, 'ground-truth' data are still required, and the Swiss Station mentioned above is now part of the network of Automatic Weather Stations that cover the Inland Ice (Steffen & Box 2001).

With respect to the dynamics of Jakobshavn Isbræ and the adjacent margin of the ice sheet, a number of American and Swiss projects have been carried out along the margin (see also the glaciology section).