DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/22

Résumé of the possibilities for the use of Greenland Inland Ice for export

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MINISTRY OF THE ENVIRONMENT

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Contents

0. Introduction

During 2005 and 2006, GEUS investigated several glaciers in West and South Greenland regarding possible freshwater extraction for bottled water export. The investigations were carried out for Greenland Home Rule, Department of Industry, Agriculture and Labour. This report, “Résumé of the possibilities for the use of Greenland Inland Ice for export” is the result of the reporting from Task 1 under the project: “Trade promotion concerning development and export of ice and water, i.e. by provision of technical and marketing knowledge within the ice and water sector”, that is carried out in a co-operation between GEUS, Greenland Resources A/S and Rambøll for Greenland Home Rule, Department of Industry, Agriculture and Labour. The résumé is based on the main report: “Analysis of glaciers from Greenland Inland Ice: Possibilities for employment of glaciers for production of ice for export of bottled water” (in Danish), GEUS 2006.

The résumé describes the need for additional data collection regarding the glaciers qualification for production of ice for bottled water production (see section 7) and selects which glaciers that are supposed to be especially suitable and that are recommended for further investigations (see section 8).

The selection of 45 glaciers and subsequent description of 43 glaciers from the Inland Ice in South and West Greenland between 60^{o} and 67^{o} N, was carried out in 2000. In addition to that 2 more glaciers were included. Concerning the localization of the glaciers and the navigation conditions in the fiords, the glacier character and the admission condition (accessibility) have been investigated from a glaciological/morphological/geological point of view (ice calving, deltas etc.) and the distance to towns, infra structure and working capacity.

A wide range of background data exists concerning the glaciers of South and west Greenland, see section 1.

The main report: “Analysis of glaciers from Greenland Inland Ice: Possibilities for employment of glaciers for production of ice for export of bottled water” (in Danish), GEUS 2006, includes descriptions of a long series of conditions concerning the glaciers, navigation, accessibility etc. A short description of these conditions is given in section 5.1.

1. Background data

A wide range of different kinds of background data are available: satellite images, aerial photos, topographical and geological maps, historical photos and descriptions, previous investigations, etc.

Satellite images

Satellite images (available from the 1960s until present-day) are useful in conducting visual surveys of remote locations, for estimations of glacier front positions, glacier morphology, landscape interpretation, ice conditions in the fiords etc.

Aerial photography

Aerial photography provides the means for accurate landscape characterization and interpretation, and as the photos are acquired as stereo-photogrammetric images, they can also be used for production of digital elevation models (DEM's). Additional photographical material exists locally from helicopter surveys. Such recent and close-up photos are very informative.

Geological maps:

The mapping effort of GEUS includes generating maps of Quaternary deposits and maps showing the underlying bedrock geology. The maps illustrate the geological conditions in the vicinity of the glaciers. The maps are available in the scales 1:500,000 (Quaternary geology) and 1:500,000/1:100,000 (bedrock geology) (GEUS, 2002).

Topographical maps:

The National Survey and Cadastre (KMS) have published a series of maps showing geography, terrain, cities and more. Saga maps cover almost all of the area investigated here in the scale 1:250,000 and these maps are available in digital form. In addition, tourist maps exist in selected areas in scales 1:100,000 and 1:75,000 and for a few areas in scale 1:20,000. Also available is an atlas of environmental sensitivity to oil spill hazards along the coast and fiords of West Greenland from 60°N to 72°N, mapping a number of factors regarding the physical environment and nature that could prove sensitive to oil spill from ships or oil drilling (Mosbech et al., 2000, 2004).

Historical photos and descriptions:

The glaciological archive at GEUS contains aerial photographs, satellite images, publications, notes etc. dating back to 1948. Results from research conducted in GEUS investigations appear in published form as well as unpublished notes and field diaries. From the late 1950s to the early

1970s, GEUS (then GGU) conducted an identification and registration of all the glaciers in South and West Greenland from Nunap Isua (Kap Farvel) and up to 71°N using the systematic approach of the World Glacier Monitoring Service for glacier registration worldwide, see Fig. 1. GEUS's glacier database follows the international standards for glacier registration (Weidick et al., 1992).

Previous investigations:
A considerable amount of knowledge has been gathered regarding the glaciology of Greenland through nearly 40 years of glaciological research and advisory activities at GEUS. The activities have included ice sheet dynamics, climate-related response and hydropower investigations. Four reports (Bøggild et al., 2000; Mayer et al., 2003; Ahlstrøm et al., 2006; Bender et al., 2003a): have been published by GEUS on the subject of mining inland ice for export purposes. Together the material in these reports constitutes the basis for the fieldwork activities planned for 2006.

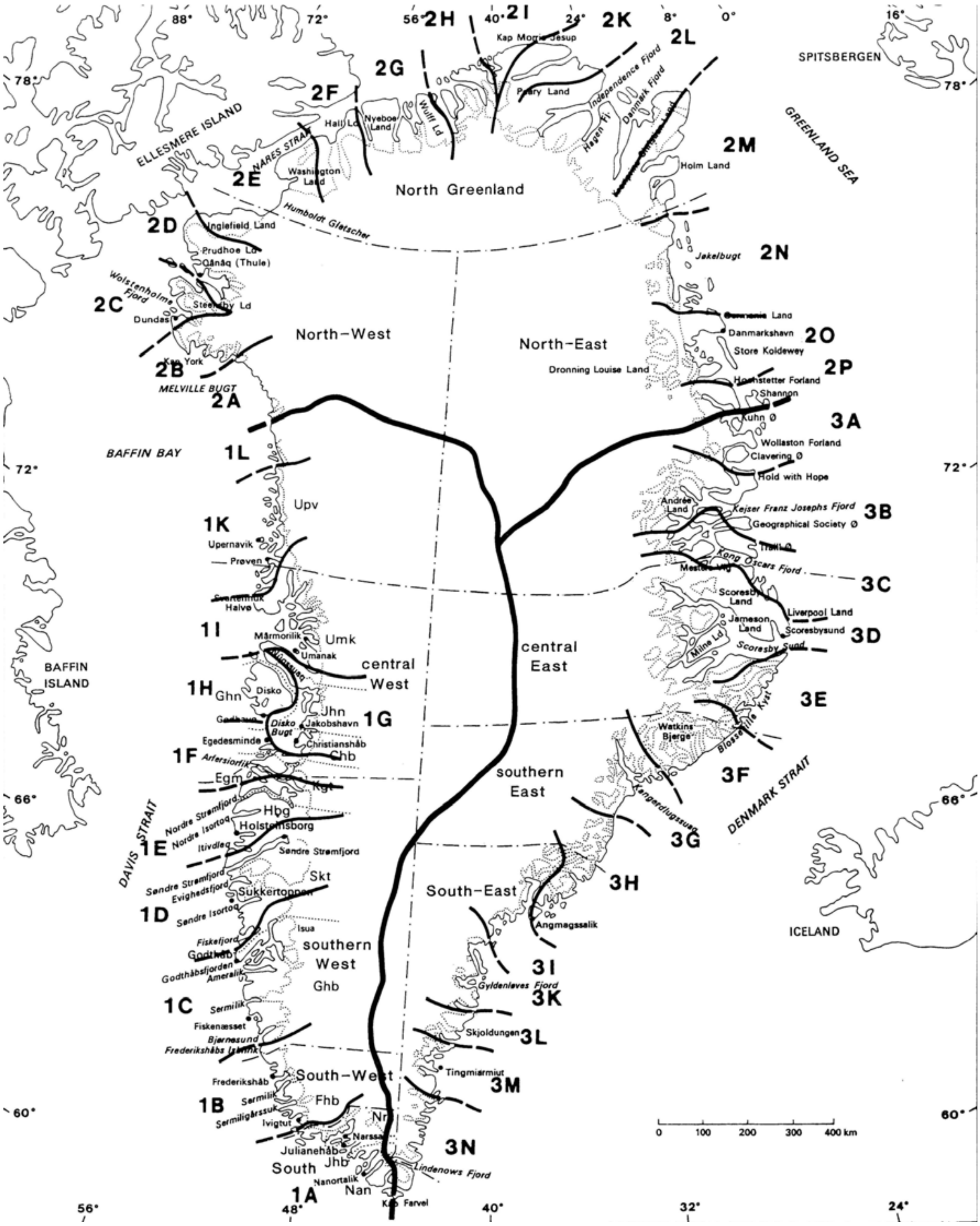


Fig. 1. Glacier hydrological main division of Greenland into districts. (After Weidick et al. 1992).

2. Inland Ice and local glaciers

The glaciers in West Greenland form about 1/3 part of the total Inland Ice of c. 1.7 million Km^2. In general terms, the ice cover in Greenland can be classified either as the Inland Ice and its outlet glaciers or as local glaciers, which in many ways differentiate from one another beyond the dimensions.

2.1 The dynamic of the Inland Ice

Owing to the size of the Inland Ice, the dome-shape and the high albedo, the ice sheet forms its own surface climate. Katabatic winds are formed. They blow in the fall direction, from the highest parts of the ice sheet towards the edge. These winds form a barrier against airborne transport of material from the surrounding land. Considerable amount of airborne dust is only found at the ice front and primary at the surface of the ice. So, the concentration of alien particles in the Inland Ice is expected to be considerable lower than the content in local glaciers.

Exotic particles that incorporate into the accumulation zone of the ice often originate from condensation nucleus for the snow particles and are typically salt crystals from evaporated sea water.

The transport of ice from the accumulation to the ablation zone takes place in a large scale by quasi-viscous floating. However, the floating causes stress internal in the ice. If or when the stress exceeds the ultimate strength of the ice crevasses will be generated. Melt water that has been in contact with the atmosphere or the terrain beneath the ice seeps into the crevasses and refreezes internal in the ice. The origin of blue bands in the glacier ice is supposed to be refrozen melt water.

The constant accumulation in the accumulation zone is compensated by ice-dynamic floating which transport the ice down to a lower level, where the melting takes place. In this process of motion, the lowermost/outermost parts of the glacier will be exposed to contact with the substratum and so the ice can pick up materials from the substratum. The ice movement itself causes a mechanical disintegration of the substratum to sediments of a large reactive surface that increases the incorporation of sediments and geochemical substances into the ice. Furthermore, seeping and refrozen melt water can increase this incorporation.

Climatic changes through time imply that the dynamic conditions for outlet glaciers from the Inland Ice are constantly changed. Consequently, dynamic isolated areas of less activity may develop. These areas are called dead-ice areas. When the uttermost ice is transgressed by younger and more dynamic ice, which by certainty is in ice dynamic contact with the ice masses behind, the origin of the ice is determined by means of the floating structure. Dead-ice areas are often caused by thrusts in the ice along shear planes. These shear planes may also be found parallel to the float direction, which means along the side of a glacier.

2.2 The character of local glaciers

Local glaciers are the designation for glaciers located outside the margin of the Inland Ice. These glaciers may vary considerably in size and form from small cirque glaciers of less than 1 km^2 to local ice sheets with areas of several hundreds of square kilometres. The accumulation zones of these local glaciers are typically located from about 700 m.a.s. and upwards. The limited size of these local glaciers combined with a relatively high precipitation means that the ice of these glaciers most likely is orders of magnitude younger than the ice from the fringe of the Inland Ice.

3. The quality of the ice

The quality conditions of the Inland Ice are the total of the chemical matters and the content of sediment in the ice. The age of the ice is an important parameter as the fact that ice, which can be dated back to time prior to the initiation of human induced pollution, is expected to be free from any matters injurious to the environment and only hold natural components.

3.1 Sediment and particles

Generally, the glacier ice from the Inland Ice is a clean natural product. However, this fact does not prevent that the ice may hold very small concentrations of fine terrestrial dust and meteoric particles deposited or fallen down from the atmosphere. Moreover, it is possible to detect ashes, soot and charcoal that have been carried to the ice by the wind. Still, some of the particles may be regarded as predominantly sterile material. However, the melting at the ice front causes the impurities to concentrate on the surface, which causes certain areas of the ice sheet surface to appear dirty. But the fact that the ice is impermeable means that the pollution of the surface only influences the quality of the ice on a limited scale.

Special geological conditions exist, where inclusions can be incorporated into the ice and reduce the quality locally. These conditions occur in connection to 1) crevasses (blue bands), 2) dead-ice and 3) shear planes in the ice. When extracting the ice, it is important to avoid the blue bands because the quality and age of blue band ice is uncertain owing to seeping water from the surface. So, the quality of consumption ice produced from blue band ice can not be guaranteed.

The occurrence of mid moraines on the ice surface indicates that basal material, picked up from the geological substratum, has reached the glacier surface. Generally, it is recommended not to extract the deepest and most marginal parts of the ice, because this ice has been close to the subjacent bedrock during floating and may hold even high concentrations of matters injurious to the environment. These matters include silt, sand and gravel and locally clay and minerals with disadvantageous properties such as high radioactivity. Based on the geological conditions it is recommended that an estimation of the surface is carried out prior to extraction. This estimation can minimize the risk for extraction of dead-ice that has been in contact with the substratum, or ice with many blue bands.

Local glaciers are expected to hold a higher concentration of alien substances that have blown in from the surrounding land. Together with the considerable younger age of the ice in local glaciers, these glaciers are characterized as a less suitable product for extraction.

3.2 Chemical conditions

The origin and – especially – the age of the ice might be the most essential sales parameters for bottled water that originates from the Greenlandic Inland Ice. However, a positive expectation for a special product is spoiled if any matters of pollution can be found in the ice or water. Although the age of the ice is determined, there is a theoretical possibility that the ice surface is exposed to pollution from modern industrial chemicals through precipitation. So, to secure a high quality of the ice, it is crucial that the ice does not contain any matters of pollution that derive from the industrialized time. Moreover, for most purposes the ice must not hold any natural but health threatens matters. Besides, it would be reasonable to accomplish identical types of analyses of the ice water that apply to natural mineral water and spring water.

It is essential to call attention to the fact that the present legislation does not allow the ice to be called natural mineral water. The ice has to be called something ells. It is recommended that legislation is established by now, which rank the ice alongside with natural mineral water concerning minimum claims for quality.

In practice this implies that the quality claims valid at present for natural mineral water, spring water and bottled / wrapped water can be used as a template for the choice of quality parameters to be used for a valuation of melted inland ice for drinking water production. The most extensive rules apply to the designation natural mineral water, while the demands for spring water and wrapped water are less. It is possible that demands identical to the Danish proclamation no. 1015 of 10/12 2003 could be used for water from the Greenlandic Inland Ice (ice water).

By Greenland ice water is understood bacteriological healthy water and the water is characterized by its natural purity. It should only be marketed as water bottled from the Greenland Inland Ice if it fulfils a series of specific conditions and comply with the maximum limits for natural found constituents and if the exploitation of the ice and the bottling of the ice water are carried out in agreement with the regulations. Treatment and admixture need to be stipulated by rules about filtrations or decantation. Any disinfectant treatment no matter the means ought to be forbidden.

It is necessary to accomplish analyses for the following:

a. Inorganic chemistry: There has to be analysed for the common components. Heavy metals or radioactive elements are not allowed to be found in the water.
b. Micro biology: The melted ice water must have a low content of perfectible micro organisms and give evidence of effective protection of the ice towards any pollution. It is especially important that the ice and the bottled water must be free from parasites and pathogenic micro organisms. At the sale, the total content of perfectible micro

organisms in Greenlandic ice water is solely allowed to arise from the normal development of the bacteriological content in the water, originating from the ice.

c. Micro pollutions: Quantifiable amounts of pesticides or pesticide remnants must not be found in the ice. Neither is it allowed to find PCB or other organic micro pollutions in the ice.

3.3 Existing chemical data

The suitability of the ice as drinking water (referring to the EU and Danish drinking water rules) has so far only been estimated in 4 ice samples from South and West Greenland:

Three samples were collected west of Narsarsuaq in South Greenland and one sample was collected from Russell's Glacier north-east of Sdr. Strømfjord. All samples have been analysed for pesticides and metabolites, PAH's, PSB's and micro biology. The analyses demonstrated pollution of the young Inland Ice in South Greenland with high concentration of organic matters injurious to the environment. Amongst other things pentachlorophenol (6.1 µg/l) and 15 different PAH's were found in concentrations of 0.014 – 0.65 µg/l. On this background, it is important to investigate if the pollution found in this young inland ice is widespread or if it only an isolated occurrence.

Moreover, the influence from global pollution on the Inland Ice was considered. Amongst other things it was concluded, that no matters injurious to the environment was found in the samples of old ice, but the younger ice contained a high level of matters injurious to the environment and a low content of micro biological embryo.

4. The age of the ice

4.1 Model calculations of the age of the ice

Directly dating methods of the ice are uncertain, difficult and expensive. So, numerical model calculation of the ice´ age has been a commonly used method though the models might be even very complicated. Generally, the age determination will become more precise as the degree of details used in the model is increased. But the age conditions of a specific outlet glacier from the Inland Ice are greatly determined by the local topographical, ice dynamical and meteorological conditions. On a larger scale and at the middle part of the Inland Ice, the local conditions are of less importance. That is why the age distribution of the Inland Ice is best described by means of large-scale models in which the ice dynamic conditions at the central parts of the Inland Ice are essential.

Based on modelling results, it can be concluded that a high accumulation rate combined with melting and basal sliding along the sole of the ice, beside the often small ice thickness is the cause that the age of the ice is generally youngest in the southernmost Greenland. So, if the age of the ice is very important it is recommended to locate the extraction as northerly as possible.

Moreover, the model calculations demonstrate that many glaciers in South and West Greenland contain ice, which is more than 5,000 years old.

5. Criteria for selection and description of glaciers

The principal criteria for selection of glaciers have been:

1. The quality (purity) of the ice must be good
2. The glacier must be located close to infrastructure
3. The glacier must be located in an area close to man power and with feasible shipping / landing conditions

The ice originating from the Inland Ice has a quality that by far exceeds the quality of local glaciers in the coastal region. This is why the outlet glaciers from the Inland Ice are in focus and the Sukkertoppen and nearby glaciers are disregarded.

Moreover, to evaluate the accessibility criteria, it has been necessary to make a determination of the distance from the glacier front to nearest fiord/sea-coast. In this way, the distance from the glacier front to the fiord/sea-coast (in nearest whole kilometre) has been measured. If the distance exceeds 10 kilometres, the glacier is considered less interesting and is disregarded. The distance between the debouchment of the glacier in the fiord and the sea-coast or a bigger town may be much longer. These distance conditions are also included in the estimations. A map of the localization of the investigated glaciers in South and West Greenland is chown in Fig. 2, next page.

5.1 Descriptions of the glaciers

Every single glacier has been described in relation to a series of different kinds of parameters. These are shortly listed below:

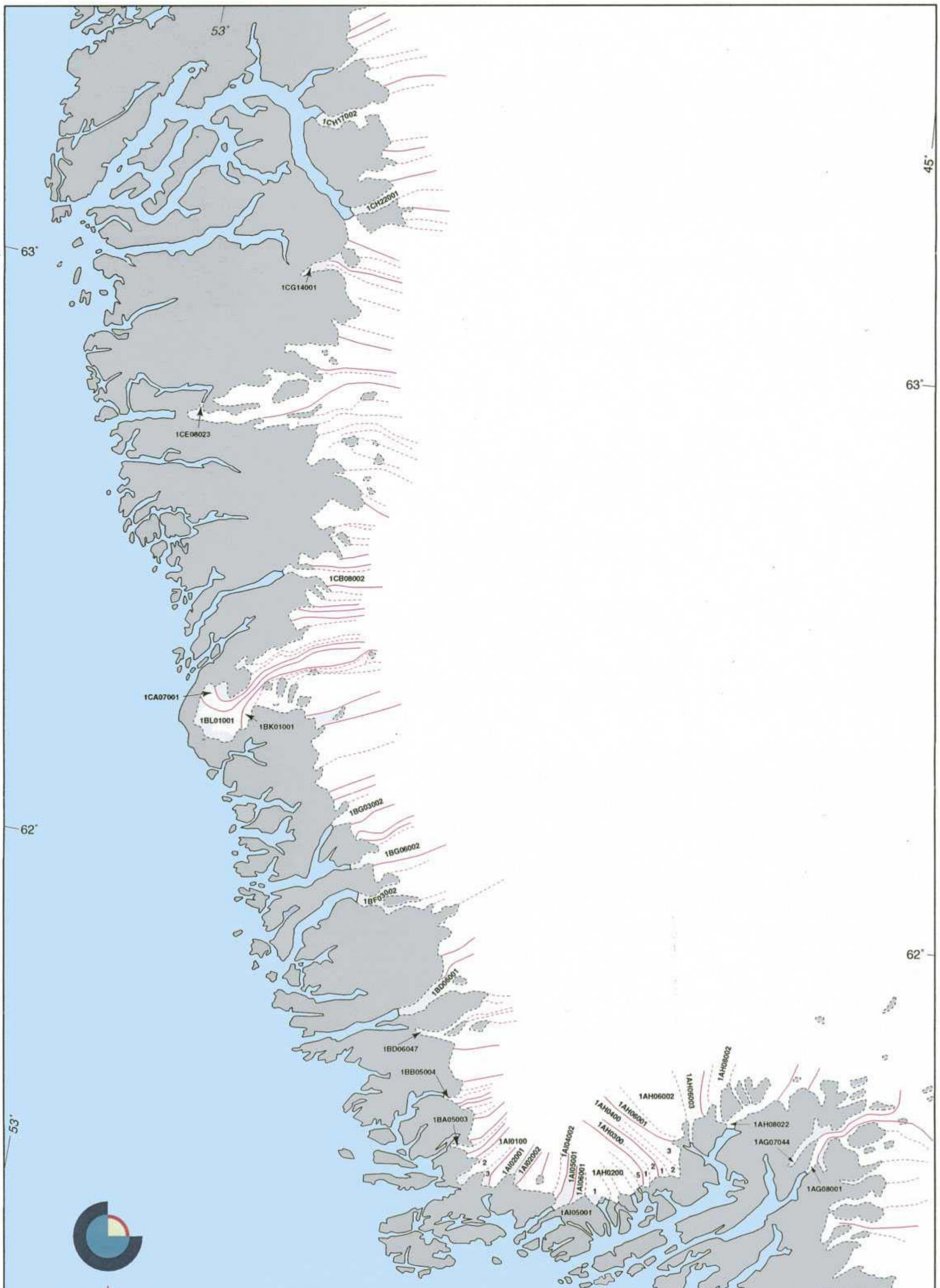
ID: Name and glacier id-code.

Aerial photographs: Year, photo-route, photo-number(s).

Satellite images: ASTER and Landsat image-number, date.

Localization: Name of nearest fiord, distance between the fiord/sea coast and glacier front, etc.

Fig. 2 (next page): Map of the localization of the investigated glaciers in Sout and West Greenland, incl. Id-codes. Scale: c. 1:2.000.000. (After Bøggild et al. 2000).


53°
1CH17002
1CH22001
63°
1CG14001
45°
1CE08023
63°
1CB08002
1CA07001
1BL01001
1BK01001
1BG03002
62°
1BG06002
1BF03002
62°
1BD06047
1BB05004
1BA05003
1AI0100
1AH06002
1AH08022
1AG07044
1AG08001
1AH0200
1AI05001
1AC07020+21
53°
45°
GEUS

Glacier co-ordinates: Geographical co-ordinates for longitude and latitude of a point on the centre line of the glacier movement in the ablation area.

Topographic maps: Number of the KMS Saga map and any tourist/hiking maps on which the glacier is located and the maps that show the accessibility conditions (fiords etc.).

Glacier delimitation: Orientation of the downward motion of the ablation area. Maximum level / highest point of the glacier (in metres above sea level, m.a.s.). Minimum / lowest point of the glacier (in metres above sea level, which is zero if the glacier debouches into a fiord). Area of the glacier surface (in square km). The area is digitized and the upper delimitation is given by the contour line 1800 m.a.s.

Glacier morphology: The condition of the glacier at the reference time is described (crevassing, icefalls, mid moraines, shear planes, dust covers, etc.). Moreover, the morphological code is given (6 number illustrating: primary glacier classification, glacier form, front characteristics, longitudinal profile, main source, glacier activity).

Glacier development: Descriptions of changes observed during the last century. The changes reflect late and recent climate changes and are important to know in case of establishment plans close to the ice border, the accessibility of the ice front and evaluations of the age conditions of the ice. Moreover, the characteristics that can be deduced from the modelling (flux conditions etc.) are mentioned.

Terrain conditions, coast and land: The conditions of the terrain around and in front of the glacier are described (landscape characterization, morphology, steepness, till covers, end moraines, materials, etc.).

The fiord: If the glacier debouches into a fiord, the conditions of the fiord are described (availability and nature of bathymetric data, tidal data, etc.).

Geology: The geological conditions of the bedrock and the overburden Quaternary deposits are described in general terms.

Accessibility: The accessibility conditions of the landscape adjacent to the glacier front are described (distance between glacier front and fiord / coast / open sea / nearest town, character of the landscape, calved ice conditions, etc.)

Other conditions: Description of any industrial and/or environmental conditions that are sensitive to or can be affected by navigations activities (oil spill), establishment of buildings/harbours (other pollution) close to the glacier (fishery, hunting, colonies of birds and mammals, archaeological sites, etc.).

Total evaluation: The descriptions are ended by a preliminary assessment of the suitability of the glacier for production of ice for bottled water, based on the existing information. Three categories have been used: Potentially suitable, partly suitable, and less suitable.

6. Discussion

6.1 The glaciers

The area of distribution and the morphology of the glaciers have been compared with the location in relation to the characters of the surrounding landscape. It makes a great difference if the glacier debouches in a fiord characterized by steep rocky coasts or if the glacier is part of the Inland Ice margin fronted by a relatively flat terrain. The conditions at the glacier front has been studied in order to judge the possibilities for establishment of houses, production plant etc. and to estimate if it is possible to pass from the area in front of the glacier to the area on top of the glacier etc.

The development of the glaciers during recent years has been taken into consideration. The increasing melting and thinning of the glaciers in South and West Greenland and the increased velocity and bulk loss to the sea are included in the investigations to find the most stable conditions in the interest of a close vicinity to production plants and thus to the supply security. The velocity of the glaciers (m/y) has been estimated from field observations and modelling. The amount of ice transported into the fiord/sea per year, the flux (m^3/y) has been modelled or found in the literature. An important point, which is a consequence of the flux, is the amount of calved ice from the glacier and thus the amount of icebergs at the front and in the adjacent fiord areas.

Based on the modelling it has been judged that glaciers of high velocity and flux are less suitable for ice production because the dynamic is to high, the movement of the glacier (advancement as well as recession) is to fast and the disintegration of the glacier into large ice blocks and ice calving occurs commonly. Correspondingly, the glaciers of low velocity and flux are considered less suitable owing to a passive ice margin of young ice from recent snowfall in the hinterland. So, the most suitable glaciers are the ones of medium velocity and flux, and where the flow lines can be traced back to the accumulation area far back in the hinterland. Even though these glaciers may have a central ice flow, the sides of the glaciers can be quiet and less deformed.

The amount of sea ice and ice in the fiord and the adjacent coastal area including icebergs brought into the area from the outside may constitute a substantial limiting factor for the shipping activities that are necessary for an export of products out of the area.

A number of the glaciers are characterized by the presence of ice-dammed lakes in the border zone between the glacier and the adjacent land. Draining off these ice-dammed lakes may cause problems concerning production of ice, because the draining may occur uncontrolled and without warning.

In front of a part of the glaciers is found an outwash plain (sandur) between the glacier front and the sea/fiord coast. The often wide and long outwash plains are characterized by systems of braided rivers constantly shifting position and alternating between deposition and erosion. The materials are made up of a mixture of all grain sizes from silt to large boulders and the dynamic active areas can be very difficult to move on and to cross.

6.2 Composition:

The quality of glacier ice concerning sediment and particles as well as chemistry is very essential for any use in a production. No information exists on the quality of the ice beside a very few analyses and the general observation of the purity of the ice. However, the existing chemical analyses show almost no contamination by matters injurious to the environment of the investigated glaciers.

The inorganic chemistry of glacier ice is almost unknown but will be important to know. For example, it has to be pointed out that many bedrocks in South Greenland have a content of radioactive elements and it is unknown to what extent this can mark the chemistry of the ice.

6.3 The age of the ice:

In order to provide an age profile of the ice in the South-western Greenland some very simple and rough estimates have been carried out earlier. These estimates show a mean residence time of about 1000 years. But these rough estimates are based on a series of assumptions and it is important to stress that the values locally may differ seriously from this age estimation. Moreover, based on the model calculations, many of the glaciers in South and West Greenland should be more than 5,000 years old. So, generally it is supposed that ice of a relatively high age can be extracted from the glaciers in question.

6.4 Accessibility and access

The (large) distance between the glaciers and the nearest towns and manpower is a strongly limiting factor for a production. Moreover, the physical accessibilities at and around the glaciers are of the utmost importance. At present it is not known, which kind of production/quarrying methods that is to be used at the glaciers. The degree of difficulties of the physical conditions that can be accepted is neither known. So, different criteria and limitations may change in importance, depending on production method, establishment possibilities and economy. Navigation on the fiords, which especially is limited by islands, depth conditions and - not the least – by ice conditions, will be the normal way of transporting the produced ice/water from the glacier to the nearest town. Presumably, this town can be considered as the Greenlandic port of disembarkation.

6.5 Other conditions

When establishing an industrial production, the conditions relating to the environment have to be considered as spillage of matters injurious to the environment and oil products may constitute a risk for the surroundings. A parameter that has to be included in the considerations is the sensitive wildlife of Greenland. Likewise, it is relevant to estimate the damage risks of the near-shore archaeological and historical sites and monuments.

6.6 Assessment

Based on the above and the preliminary assessments for each glacier during the analyse the results were:
Among the 42 glaciers, 12 were estimated as potential suitable for ice production, 6 glaciers were judged as partly suitable and 24 glaciers were considered less suitable. Afterwards, the further estimation and assessment has been fulfilled among the 12 potentially suitable glaciers (see section 8).

7. Additional data collection

A series of criteria, parameters and physical conditions are decisive for whether or not an outlet glacier is suitable for extraction for ice export. These conditions concerning accessibility, morphology and stability have to be cleared up and described for each locality by means of further interpretations of satellite images and maps and by data collection in the field as well. Typical, the field work at each locality is initiated by navigating into the chosen areas, whereby many of the parameters described below can be collected. On land adjacent to the glacier, the remaining information is collected. In some cases it will be necessary to fly up on the top of the glacier.

The interpretation of the glaciers has shown that the distance and the accessibility to the chosen glaciers presumably constitute a large problem for extraction of ice. But conditions such as ice dynamic and occurrence of dead-ice are important factors.

The analyse of the 12 potentially suitable glaciers clearly demonstrate the need for supplementary data collection before it is possible to give more qualified statements of the production possibilities at the specific localities.

Since it would be inappropriate and economic impossible to accomplish data collection from all 12 potentially suitable glaciers, 4 glaciers have been pointed out for further investigations (see section 8). The subjects relevant for preparing, collection and reporting under option 1 are described in the following. The tasks include data collection and data classification at GEUS prior to or after the fieldwork in July-August 2006. The chronology of the tasks will follow and respect the most suitable solution for the total job.

7.1 Accessibility, terrain and geology

There is a need for collection of geological and geomorphologic detail information on the localities. This information is necessary for a judgment of the possibilities for establishment of a production plan with a base in the neighbourhood of the glacier. This is only possible by means of field data/observations. But from the existing data it is possible to construct digital elevation models (DEM's) that later on can be updated with field data. The collected data will form the background for technical and economical considerations regarding production plans including any natural conditions that may reduce the possibilities for a production.

Concerning accessibilities, it has to be examined in detail, in which way it is possible to emerge to the glacier, and which limitation may occur from fiord ice, ice calving etc. Moreover, data concerning fiord/coastal conditions in relation to harbours, towns and man power have to be collected. Depths data of the fiords are partly accessible but it has to be settled precisely how many data exists and in which way these data are accessible.

It is important to know the frames for the demands to navigation conditions, such as number of months, where navigation is possible, the maximum ice thickness in the wintertime, the risk of pack ice, the dimension of ice calving, etc. With respect to harbours and anchoring places, information about depth and anchoring conditions and demands concerning establishment of quay are important.

Moreover, it is important to know the physical demands for land-facilities, such a road construction (length, quality), the risks of ice-cored moraines and the possibility for establishment of a road on the very ice surface.

Prior to or after the fieldwork, data from satellite images concerning the duration of the sea-ice in the winter months in the innermost parts of the fiords should be collected. Data showing indication of “tsunami” risks and time series for pack-ice (for quays) do not exist at present and have to be collected as well. Digital elevation models (DEMs) for each of the 4 localities in question are prepared owing to analyses of icefall, critical thresholds, etc. Satellite images may be draped on the models later on. Models are to be evaluated concerning dynamic activity and perhaps also the calved ice production that are important to estimations of the infra structure and navigation conditions. Moreover, the coastal conditions shall be analysed from satellite images.

During the fieldwork, the navigation conditions are described as detailed as possible. The possibility for establishment of quays (coastal morphology, geology) is described “on location”. The same is done concerning the possibility for establishment of a road between the coast and the glacier (topography and the risk for ice cored moraines) and for establishment of a road on the very ice (ice movement and melting). Finally, a descriptive field report is prepared from each locality visited, including an evaluation of trim line (recession since the Little Ice Age), special characteristics of the ice surface that indicate future sensitivity to recession etc. The report is useful if the priorities are changed later on, or if a producer wishes a further evaluation.

7.2 Glacier morphology and dynamic

On the localities, the glacier front is characterized, described and photographed and the age conditions and ice quality are estimated. Additional considerations concerning the movements of the glacier (advancing – recession) are judged from indications from the surrounding landscape and trim lines, in addition to interpretations from air photos and satellite images. New satellite images will be analysed in detail and considerations will be made concerning any influence on the glacier from climate change.

Prior to or after the field work, high-resolution satellite images are interpreted concerning information on the degree of crevassing. This is important in relation to pollution of the ice, identification of mid-moraines, visible shear planes etc. Crevasses and floating structures are mapped by means of satellite images of utmost quality (resolution *c*. 1 m) all the way up to the equilibrium line (20 – 50 km) and the amount of dust blown in from the surrounding landscape is estimated by means of reflection conditions (albedo) throughout the entire ablation zone.

During field work, at the potentially most suitable localities (for ice breaking), notes about the ice morphology are taken, including information on the glacier movement and the localization of blue bands, crevasses and other “dirty” areas. This gives a broad idea of the homogeneity of the ice. Owing to the movements of the glacier, the descriptions can only be temporary. Moreover, the locality is documented by means of photographs and videos. The photographing can be repeated later on, if the locality is to be used. This repeated photographing helps to evaluate how the crevasses are generated and closed again.

7.3 Quality conditions

The content of sediment and other foreign matters is to be evaluated at the locality, but regular analyses of the content must be performed on ice samples in laboratories. This is very necessary as no such analyses are available. The chemical composition can only be determined in laboratories by means of analyses of inorganic and organic components. Only a few analyses of the organic parameters are available, so a number of analyses are very necessary for a judgement of the suitability of the glacier. Most probably, the same samples can be used for analyses of sediment content as well as chemistry, if the samples are big enough. The number of samples that has to be collected depends on the individual glacier, but a minimum of 15 samples per glacier are necessary. The localization of sampling positions is decided on location.

The glaciers have an original chemical composition together with a potential content of chemical matters injurious to the environment. Crevassing of the glacier causes dirt from above to penetrate into the glacier. The dirt may include pollution transported to the area from distant places and the pollution of the ice is caused by the descent and re-freezing of dirty melt water. The entrance of till from the bottom and the sides of the glacier into the ice can cause deterioration of the ice quality, similar to windblown dust on the ice surface. The presence of shear planes and dead-ice can result in lower ice quality. Owing to the mixing of ice with materials and melt water, it will be essential to investigate the old ice for a long series of known matters injurious to the environment. For instance, the analyses could include *c*. 20 different PCB´s and PAH´s, the pesticides glyphosat and pentachlorophenol, plus *c*. 30 other pesticides and breakdown products that are included in the Danish pesticide monitoring programme NOVANA. The precise specification of which analyses that should be accomplished ought to be coordinated with the requirements of the expected most important exporting markets (EU, USA, Japan).

During field work, ice samples are collected for determination of the ice quality and local quality variations. The positions of the sampling sites are measured by GPS and all information concerning the sampling is noted. Samples of about 3 litres in size are collected.

In the laboratory, the samples are analysed for relevant parameters concerning the use as drinking water (drinking water quality): inorganic chemistry, pesticides and metabolites, PAH, PCB, micro biology, sediment content, other alien substances. The analyses will be performed in an accredited laboratory and at GEUS.

7.4 Age.

A direct method for age dating does not exist, but for every single locality the age will be estimated / modelled. It is possible to use numerical model calculations for an estimation of the age of the ice.

Estimation of the age will be grounded on a series of simplified assumptions about the ice floating and climate / precipitation conditions back in time based on field observations, maps etc. However, this involves a certain amount of uncertainty. Therefore, it is essential to come to a decision on the degree of importance this parameter is to the product that is to be sold. If it is an important parameter, the requisite resources should be earmarked for elaboration of a method.

7.5 Stability and supply guarantee

At several locations, the border zone of the Inland Ice in South and West Greenland is marked by a pronounced thinning. The ice margin north of Bredefjord, by way of example, has receded about 5 kilometres or more during the last decades. If long investments are to be expected, it is essential to estimate the supply guarantee. Knowledge of the ice border stability can shortly be classified into two categories, the historical variations and the possible future variations. The Inland Ice is known globally, and it is to be expected that questions concerning the stability of the Inland Ice will be asked from foreign investors. Existing knowledge shows that ice calving glaciers are very sensitive to climate variations. For example, at some places the thinning is more than 10 metres per year and the ice front may recede several kilometres during a single year or a few years. Model results have shown that if a glacier has certain geometry, the receding process may accelerate itself and reach several kilometres in a few years. A documentation of all this should be available.

The historical variations at the 4 selected localities are investigated by means of glaciological analyses. Recent research results and glaciological data are examined in order to illustrate how much the fronts are able to melt back. Simple model scenarios for each locality are prepared, after which the recessions and fluctuations of the ice border can be estimated. The melting and thinning may be draped on an eventual elevation model.

It is examined whether it is relevant and possible to map critical thresholds and other kind of input data (for the model calculations) by means of ice radar measurements of the bottom/ground. Any signs of changes of the ice border and the consequences are described and measured.

7.6 Data collection and report

For each of the four glaciers, all collected data are put together in a report, in a way that allow extraction of conclusions concerning the investigated glaciers as well as more general aspects regarding ice production conditions. The final report will be available in an analogue and a digital version including all obtained information in text, tables and maps. The obtained data will be put into the database that is established under Task 2.

8. Selection of glaciers for field investigations under option 1

The area north of Bredefjord and Nordre Sermilik in south Greenland is most attractive because the margin of the Inland Ice borders on to the coast with large areas of ”pure” ice and without the strong calved ice production that otherwise characterize the head of many fiords. The following glaciers have been designated from this region: Western Kangerluarsuk Bræ (1 AH 03001), Ilorlliit Sermiut (1 AH 02005), Qalerallit Sermia (1 AH 02001), No name (1 AI 06001) and Sermilik Bræ (1 AI 05001).

Other localities with fewer suitable glaciers are found along the coast toward north: Arsuk Bræ (1 BB 05004) in Arsuk fiord, Nigerlikasik Bræ (1 BG 06002) in Kvanefjord/Nigerlikasik fiord, Avannarleq Bræ (1 1 BG 03002) in Kvanefjord/Avennarleq Fjord, Nakaissorsuaq (1 CB 08002) in Bjørnesund, Narssap Sermia (1 CH 17002) in the inner part of Godthåbsfjord and Russell’s Glacier (1 DG 02002 +01) at Sdr. Strømfjord

Based on these possibilities, the four glaciers below are recommended for further investigations under Option 1. The relevant glaciers represent outlet glaciers from three areas: South Greenland north of Narsaq, the middle region around Frederikshåb Iceblink and the western region around Nuuk and Sdr. Strømfjord. So, the glaciers are geographically spread over the entire analysed coastal area (Fig. 3, next page).

A. Sermilik Bræ, Sermilik fiord, south Greenland.
Sermilik Bræ was chosen on account of the accessibility from Sermilik fiord, the modest calved ice production and the medium velocity and flux. Moreover, the distance to Narsaq and other towns in south Greenland is relatively modest. Besides, it is pointed out that the glaciers Ilorlliit Sermiut and Qalerallit Sermia, situated a little toward the north of Bredefjord, have been taken into consideration and ought to be visited for a provisional description.

B. Nigerlikasik Bræ, Kvanefjord/Nigerlikasik fiord, west Greenland
Nigerlikasik Bræ was chosen because of the accessibility from Nigerlikasik fiord (side fiord to Kvanefjord) and a modest calved ice production. The nearest town Paamiut (Frederikshåb) is located in a presumably suitable distance.

C. Narsap Sermia, Godthåbsfjord, west Greenland.
Narsap Sermia in Kangersuneq ice fiord/Godthåbsfjord was chosen because of the glaciological conditions and the vicinity to Nuuk.

D. Russells Glacier, Kangerlussuaq, West Greenland.

Russell Glacier was chosen because of the accessibility of the glacier and the vicinity to the nearest town, Kangerlussuaq, located only 35 km from the glacier.

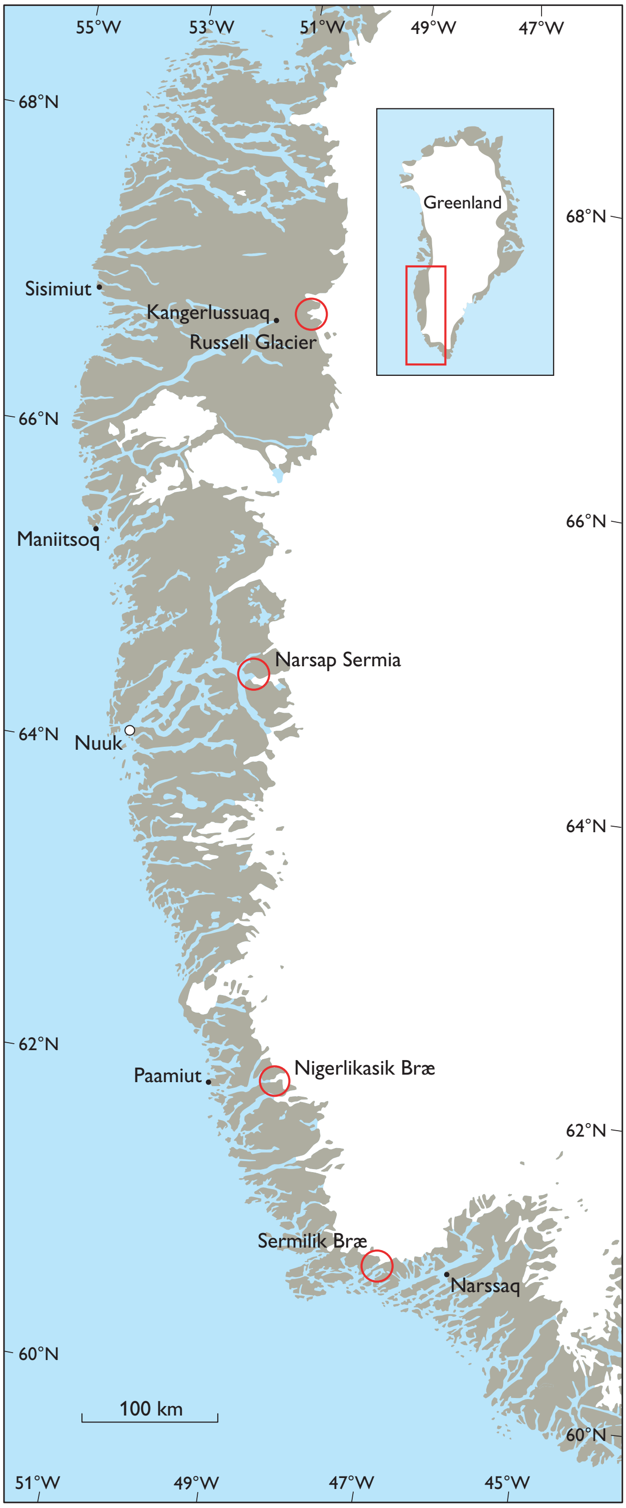


Fig. 3. Map showing the location of the 4 glaciers recommended for further investigations under Option 1.

9. Final remarks

It is possible that more outlet glaciers from the Greenlandic Inland Ice can be used for ice production. It is striking that only little information exists about the important parameters that have to be known before a decision of starting of a production can be taken. Therefore it is essential to gather detailed information about the four selected potentially suitable glaciers that can be used in the considerations about a production. Moreover, the data collection will serve as a model for an investigation concept for data collection from other localities.

10. Literature

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