DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2006/25

Cruise report: The Galathea 3 expedition to Greenland 2006

Holocene fjord and shelf processes in West Greenland: a record of environmental and climatic change

Naja Mikkelsen, Ole Bennike, Birger Larsen,
Niels Nørgaard-Pedersen, Majken Djurhuus Poulsen,
Aaju Simonsen & Esajas Arqe

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2006/25

Cruise report: The Galathea 3 expedition to Greenland 2006

Holocene fjord and shelf processes in West Greenland: a record of environmental and climatic change

Naja Mikkelsen, Ole Bennike, Birger Larsen,
Niels Nørgaard-Pedersen, Majken Djurhuus Poulsen,
Aaju Simonsen & Esajas Arqe

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

Cruise report:
The Galathea 3 expedition to Greenland 2006

Holocene fjord and shelf processes in West Greenland:

a record of environmental and climatic change

Naja Mikkelsen, Niels Nørgaard-Pedersen, Ole Bennike, Majken Djurhuus Poulsen,
Aaju Sofiaraq Simonsen, Birger Larsen and Esajas Arqe

Cruise report:
the Galathea 3 Expedition to Greenland 2006

Summary

The project *Holocene fjord and shelf processes in West Greenland: a record of environmental and climatic change* was selected to be part of the Galathea-3 expedition during the expeditions circum navigation of the world from August 2006 to April 2007. The invitation to participate in the expedition was based on a project proposal (Appendix 1) submitted to the Danish Expedition Foundation in February 2006.

Eight members of the project group embarked *Vædderen* in Narsarssuaq on August 25th and disembarked in Nuuk on September 8th 2006.

The cruise resulted in a large harvest of sediment cores, and was a great success.

Working areas

Work was conducted in four areas: Narsaq Sund/Bredefjord, Holsteinsborg Dyb, Amerloq and Godthåbsfjord (Fig. 1). The core positions in Narsaq Sund are close to Norse and Inuit ruins, and close to the Ilimaussaq intrusion. Holsteinsborg Dyb was the main target of the Århus group. Amerloq was chosen during the cruise, because we expected strong wind on the shelf. The fjord is a rather small threshold fjord just south of Sisimiut. Godthåbsfjord is a major fjord system with large islands. The bathymetry is characterised by deep basins separated by bedrock highs. Major ice marginal deposits were found.

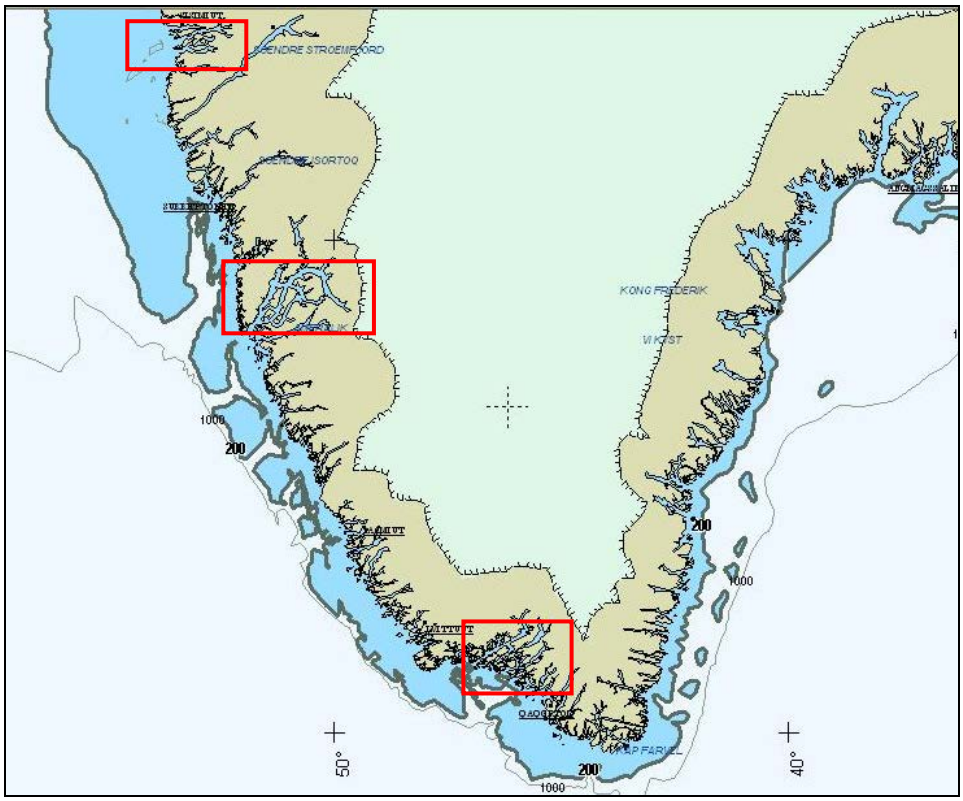


Fig. 1. Map of Greenland showing the three main working areas.

Methods

Brutalis box corer

The “box” is a 30 cm diameter steel tube (Fig. 2). When the corer reaches the sea floor, a shovel closes the bottom of the corer, and cores up to 55 cm long can be collected. The sea floor may be almost intact. The uppermost surface sediment (0-1 cm) were sampled and the box corer sub sampled by pressing three plastic tubes down into the sediment. Whole cores were shipped back to the laboratory.

Gravity corer

The gravity corer on *Vædderen* (Fig. 3) was used to collect sediment cores up to 6 metres long, with a diameter of 12 cm. The corer has a core head with a 750 kg lead weight, a steel tube with a PVC liner and a core catcher. On top of the corer is a one-way valve that prevents the top sediment to be flushed out of the tube when the corer is taken up through the water. The cores were cut in one meter long sections for shipment back to the laboratory in Copenhagen. Sub samples were collected at one metres interval for preliminary analyses on board.

Fig. 2. The ‘Brutalis box corer’ proved valuable during the cruise in the Greenlandic waters. The smaller regular box corer was too light to be used at the deeper waters where fairly strong currents distorted the descent of the corer at great water depths.

Fig. 3. The 6 meter long Gravity corer was used subsequent to the los of the piston corer. The gravity corer worked without problems and provided undisturbed cores in the soft sediments. At the shelf edge and at the shallow sill at the entrance to the Godthåbsfjord system the gravity core was unable to penetrate the consolidated and winnowed sediment.

Piston corer

The NIOZ piston corer is a sampling equipment to take sediment cores up to 12 metres long, with a diameter of 8.5 cm. It includes a corer head with a 1.5 tons weight and steering fins, a steel tube, a liner and a piston with a one-way valve below. The valve prevents the plastic liner to collapse when taking the corer out of the sediment. The corer is equipped with a 100 kg free-fall trigger, and coring begin when the piston is just above the sediment surface, and ends when the core head has reached the piston. The trigger is equipped with a small gravity corer that collects cores up to 74 cm long. This corer was lost at the first coring site due to failure in the hydrolic system.

Multibeam

A multibeam echo sounder was used for high precision bathymetrical mapping. The data handling was conducted by Morten Sølvsten and Henrik Holm from Søopmålingen Grønland. The multibeam data can be converted into side scan images.

Seismic equipment

It was planned to use an X-star chirp sonar for high-resolution, shallow seismic profiling. However, the sonar did not work properly, this equipment was not used. For deeper penetration, an airgun and

a 96 channel, 600 m long streamer were used. The air gun was fired twice with a second shot 52 ms after the first. Data handling was conducted by a team from Aarhus University, under the supervision of Holger Lykke-Andersen.

Fig. 4. The cores were cut in one meter segments for shipping back to the laboratory in Copenhagen.

Narration

The weather was fairly stabel during the cruise period, with calm weather or low wind velocities. Only two short intervals with velocities over 10 m/sec were encountered. Temperatures ranged between 5 and 10°C. Towards the end of the cruise some rain was encountered.

Thursday 24th August

At 9 a.m. *Vædderen* arrived in Narsarsuaq (fig. 5). After a short briefing, a tour was made to Qasiarsuk, the former Brattahlid, where Erik the Red settled more than 1000 years ago. The Norse ruins and a reconstruction of Tjodhilde's church and a Norse long house was visited. Minik Rosing from the Geological Museum in Copenhagen guided a geological tour, where different lava types from the Gardar Province was studied.

In the evening, the containers were unpacked and the two X-star racks were placed in the seismic container.

Fig. 5. The 112 m long navy ship Vædderen, which is the research platform for the Galathea-3 expedition

Friday 25th August

In the morning captain Carsten Smith conducted a small helicopter reconnaissance to check the ice cover in Bredefjord. In spite of the late time of the year, the inner and middle parts of the fjord is still packed by ice bergs. The ship left Narsarsuaq in the afternoon and headed for Narsaq Sund, the strait between Bredefjord and Tununliarfik (Fig. 6).

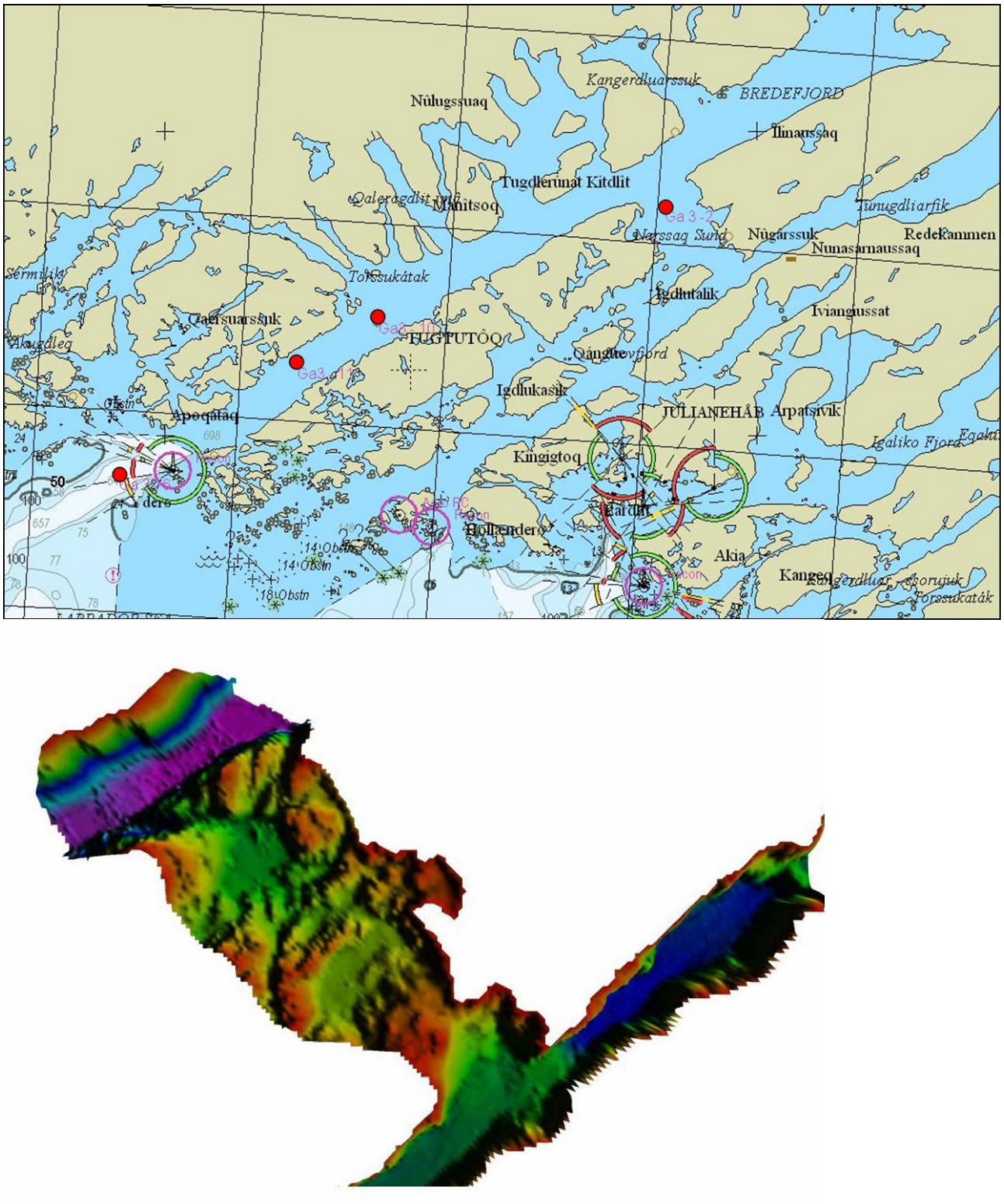


Fig. 6. Map of the Narsaq Sund and Bredefjord area with the main coring stations. Multi-beam image of the bathymetry in Narsaq Sund.

The piston corer was assembled to be used on the star board side of the ship. The work was led by Jack Schilling from NIOZ, the Netherlands. At the same time, two samples were collected using a small dredge. The samples were collected in two basins that were mapped by multibeam echo sounder in 2005.

On the first position, stones and boulders dominated the sample, but on the second position mud dominated, and it was decided to collect cores here.

In late afternoon the piston coring equipment was ready. During the operation, the corer as transferred from the crane to a small which, and finally to the main which of the ship. During this operation the corer was lost (Fig. 7).

The gravity corer was assembled, and two cores were taken The X-star was tested, but with poor results. However, the air gun seismic equipment run by Aarhus University worked as planned.

Fig. 7. The 12 m long Piston Corer was lost at the first coring site due to failure in the winch system.

Fig. 8. Collecting surface sediment from a Brutalis box core.

Saturday 26th August
Vædderen collected water samples from deep waters off the coast.

Sunday 27th August
Vædderen sailed back towards the coast. Box cores and gravity cores were collected off the mouth of Bredefjord and in the outer part of Bredefjord (Fig. 8).

Monday 28th August
Steamed north.

Tuesday 29th August
The Århus group conducted seismic work from the continental slope towards the NE of Sisimiut, mapping the Holsteinsborg Dyb.

Wednesday 30th August
The Århus group continued the seismic mapping.

Thursday 31st August
The Århus group continued the seismic mapping. "Stamp day" – on behalf of the Greenland F….. Stamps were placed on 300 post cards. Two stamps on each. One of the stamps is a new Greenlandic Galathea-3 stamp.

Friday 1st September
The Århus group continued the seismic mapping of the Holsteinsborg Dyb region.

Saturday 2nd September
Fine morning with a fantastic view of the coast. Took in the air gun and the streamer, and collected sediment samples. The first attempt was at the outer shelf, where "old" dipping layers are exposed near the sea floor. The bottom consisted of sand, which prevented cores to be collected.

Vædderen continued to the inner part of Holsteinsborg Dyb, where sediment bodies were located on the seismic profiles. Box cores and gravity cores were successfully sampled at two locations.

At 3 p.m.Vædderen sailed into Sisimiut harbour and saluted three times, on the occasion of the city's 250 years anniversary. After that Vædderen continued to the fjord Amerloq south of Sisimiut, where multibeam measurements and echo sounding was conducted during the night.

Sunday 3rd September
Spent the day in Sisimiut.

Monday 4th September
Seismic profiling in Amerloq. The fjord has a threshold to the west and a basin to the east. At two positions, box cores and gravity cores were collected (Fig. 9).

Tuesday 5th September
During the night and the morning, *Vædderen* sailed south to the Godthåbsfjord. In the early evening, seismic profiling began at the mouth of the fjord. Here a marked ice marginal line was located. Farther into the fjord system, several basins were located (Fig. 10).

Wednesday 6th September
Continued seismic profiling in the morning, and located several small basins. In the afternoon, *Vædderen* anchored off Kapisillit, and an excursion was made to the ice fjord Kangersuneq and to Kapisillit. A new test of the X-star was made, but with poor results.

Thursday 7th September
Coring was conducted in a small basin in central Kapisillit Fjord. A six meter long gravity core was recovered. The sediments consisted of a silt-rich mud with some dropstones in the upper part.

The next station was in central Godthåbsfjord. A 50 cm long Brutalis core was taken; this core contained clay-rich sediment with some dropstones. Two attempts to collect gravity cores failed, perhaps due to sandy sediments. The final station was at the fjord mouth, where a box core contained stones and coarse sand. Finally we continued to Nuuk.

Friday 8th September
In the morning he ship was abandoned.

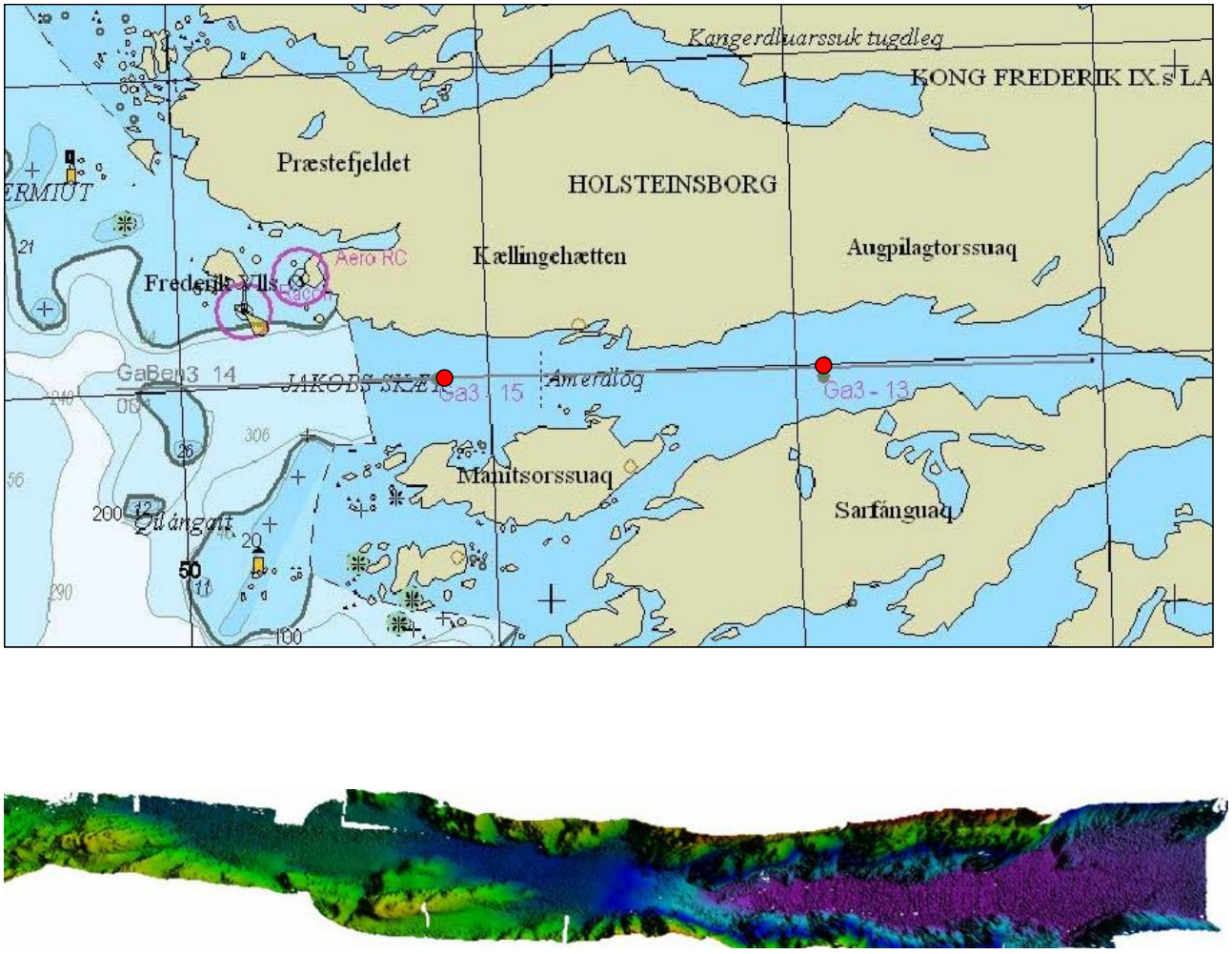


Fig. 9. Map of Amerloq fjord and main coring stations. Below: Multi-beam image of the fjord bathymetry.

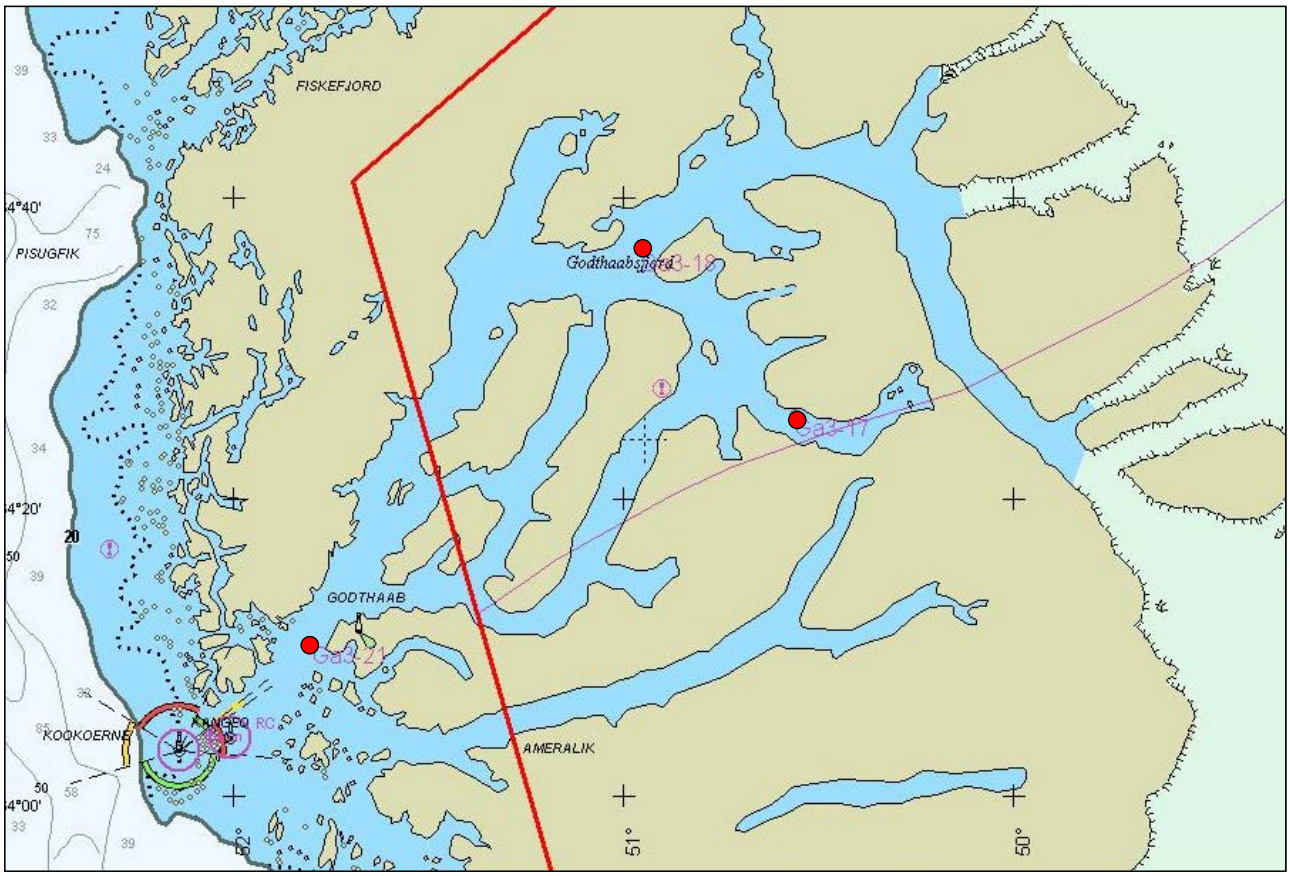


Fig. 10. Map of the Godthåbsfjord complex where a detailed seismic survey and multibeam survey was undertaken and main coring stations.

Core No.	Date	Longitude	Latitude	Gear	Depth (m)	Recovery (cm)
bag sample	26-08-2006	60 55.179	46 06.365	Dredge	156	full
bag sample	26-08-2006	60 56.333	46 09.388	Grab	280	full
-	26-08-2006	60 56.637	46 09.684	Piston corer	272	0
G3-1	26-08-2006	60 56.236	46 09.293	Gravity corer	267	245
G3-2	26-08-2006	60 56.200	46 09.300	Gravity core	270	557
G3-3	27-08-2006			Grab	690	empty
G3-4	27-08-2006			Grab	700	almost empty
G3-5	27-08-2006	60 42.943	47 04.531	Box corer	666	bag sample
G3-6	27-08-2006	60 42.960	47 04.583	Gravity corer	666	ca. 550
G3-7	27-08-2006	60 42.871	47 04.496	Gravity corer	653	527
G3-8	27-08-2006	60 50.544	46 38.475	Box corer	635	ca. 45
G3-9	27-08-2006	60 50.650	46 38.232	Gravity corer	633	0
G3-10	27-08-2006	60 50.678	46 38.292	Gravity corer	633	49
G3-11	27-08-2006	60 48.465	46 46.519	Gravity corer	650	500
G3-12	04-09-2006	66 54.415	53 16.785	Box corer	570	50
G3-13	04-09-2006	66 54.167	53 16.818	Gravity corer	536	526
G3-14	04-09-2006	66 54.145	53 35.276	Box corer	321	48
G3-15	04-09-2006	66 54.136	53 35.447	Gravity corer	322	553
G3-16	06-09-2006	64 25.569	50 33.468	Box corer	193	30
G3-17	06-09-2006	64 25.577	50 33.547	Gravity corer	199	ca 550
G3-18	06-09-2006	64 36.575	50 57.087	Box corer	562	55
G3-19	06-09-2006	64 36.602	50 56.720	Gravity corer	562	bag sample
G3-20	06-09-2006	64 10.414	51 47.759	Gravity corer	559	bag sample
G3-21	06-09-2006	64 10.414	51 47.759	Box corer	269	bag sample

Tabel 1. Station list and sample recovery

Fig. 12. A good harvest of sediment cores.

Preliminary results

Sediments and foraminifers

No cores were split on board *Vædderen*, but samples were collected at one meter interval when the cores were cut in one meter long pieces for shipment back to Denmark (Fig. 11, 12; Tabel 1). The sub samples were wet-sieved on a 63 micron-meter sieve and the coarse fraction was examined using a dissecting microscope (Fig. 13). In general, the samples consisted of fine grained sediment. However, different sediment types were found in the fjord and shelf areas. The cores from Narsaq Sund are dominated by mud with a high content of organic material. The sediments are rich in benthic calcareous foraminifers such as *Nonionella labradorica, Megaglobolуides, Casidulina reniforme, Casidulina neoteretis, Casidulina reniforme* and *Elphidium excavatum* forma *clavata* . In Bredefjord, the sediments consist of layers of sand and clay with few foraminifers (mainly *Casidulina reniforme* and *Elphidium excavatum* forma *clavata*). The preliminary analyses indicate that the major parts of the sediments are deposited by turbidity currents.

The cores from Amerloq are fine grained blackish marine gyttja extremely rich in gas. This indicates oxygen poor bottom waters, a high supply of organic matter and limited ventilation. One core was collected in the deep eastern basin, and one core farther west closer to the threshold, and at shallower water depth. The core from the deep basin had the highest gas content. Most samples from both cores contained a limited amount of benthic foraminifera. A single shell of the subarctic bivalve *Megayoldia thraciaeformis* was noted and picked out for AMS radiocarbon dating.

The cores from Godthåbsfjord represent deep basins and threshold areas. A 5.5 m gravity core from a minor basin in the inner part (Ga3-17) contained greyish silty muds with some dropstones in the upper part. At another core site in a deeper basin we only got a full box core (Ga3-18), whereas two gravity coring attempts were unsuccessful. Preliminary investigations of subsamples indicate only a very rare occurrence of benthic foraminifers *Casidulina reniforme* and *Elphidium excavatum* forma *clavata*.

Fig. 13. The sediment laboratory was established in one of the six containers. The 6 m^2 laboratory space was a bit jammed at times as at least 4 different projects used the lab space in the container at various times.

Seismics

Seismic data were collected from the Holsteinborg Dyb - a transverse channel that crosses the banks on the shelf at the latitude of the polar circle. The 100 to 400 m deep channel was the main target for the activities of the Aarhus group on this part of the Galathea expedition. The trough ends in a coast parallel channel. It has been eroded in the sediments just off the resistant basement – just like the deep parts of Skagerak and Kattegat.

This was nicely demonstrated by Holger Lykke-Andersen's new seismic profiles. The shelf was formed in part by out-building of the continental slope.

At many sites, plough marks from ice bergs are seen on the surface of the shelf. Another interesting aspect is that the inner part of the Holsteinsborg Dyb has been partly filled by Quaternary sediments.

Research and education

An important goal of the project has been to strengthen and develop research collaboration within the natural sciences and the humanities between Denmark and Greenland – and not least to support research education and recruiting in Greenland of young Greenlanders.

The Climate change project group has therefore included two young Greenlandic students and a student from the primary school in the small community Ittoqqortoormiit on the east coast of Greenland (Fig. 14). The two geology students have participated in all aspects of the scientific work onboard and have collected material for the bachelor work at the university. The school student has participated in the work on deck while retrieving sediment cores – and has participated in other aspects of the work on board. He was obliged to make presentations upon return to his school – and this will hopefully raise the awareness of the importance of natural sciences among these young people living in a fairly isolated world with respect to education.

Fig.14. Esajas Arqe, Majken Djurhuus Poulsen and Aaju Sofiaraq Simonsen

Acknowledgement

Funding for the Galathea project *Holocene fjord and shelf processes in West Greenland: a record of environmental and climatic change* was received from the Bikuben Foundation, the Commission for Scientific Research in Greenland, the Royal Greenlandic Foundation and the Geological Survey of Denmark and Greenland. This funding which made the participation in the Galathea endeavour possible were gratefully acknowledge. The cruise participation of the two Greenlandic students Aaju Simonsen and Majken Poulsen was made possible through the generous donation by the Royal Greenlandic Foundation where as the participation by the Greenlandic student Esajas Arqe from East Greenland was made possible by the very generous donation from the Bikuben Foundation.

The cruise participants of the Galathea Leg 3 from Narsarsuaq to Nuuk August 25 – September 8 gratefully acknowledge the possibility to participate in this highly inspiring and rewarding cruise. The scientific and cheerful support by the cruise Leader, professor Minik Rosing, was invaluable as was the support, help and friendship from the crew of the HMSD *Vædderen* represented by Captain Carsten Schmidt. The never failing enthusiasm of these persons as well as our scientific colleagues in helping us reaching our scientific goals will be remembered with happiness.

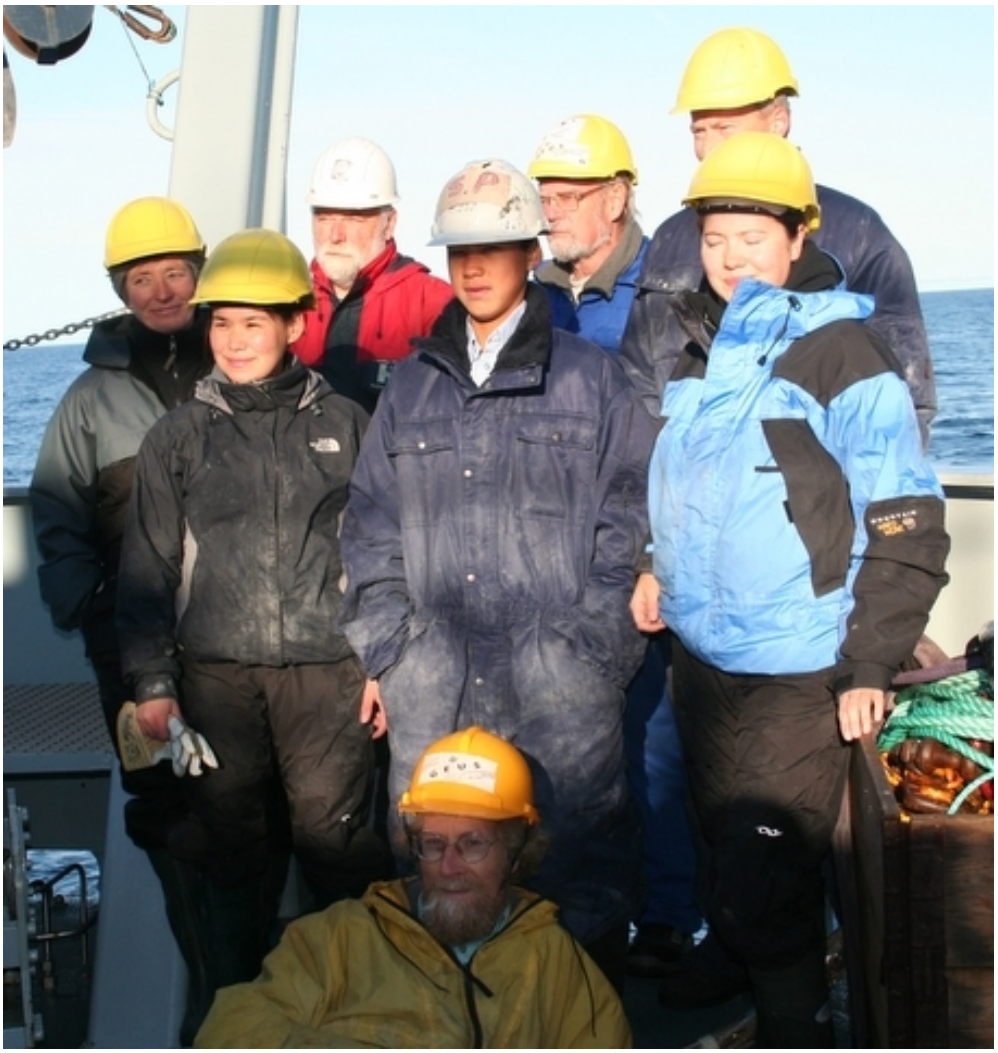
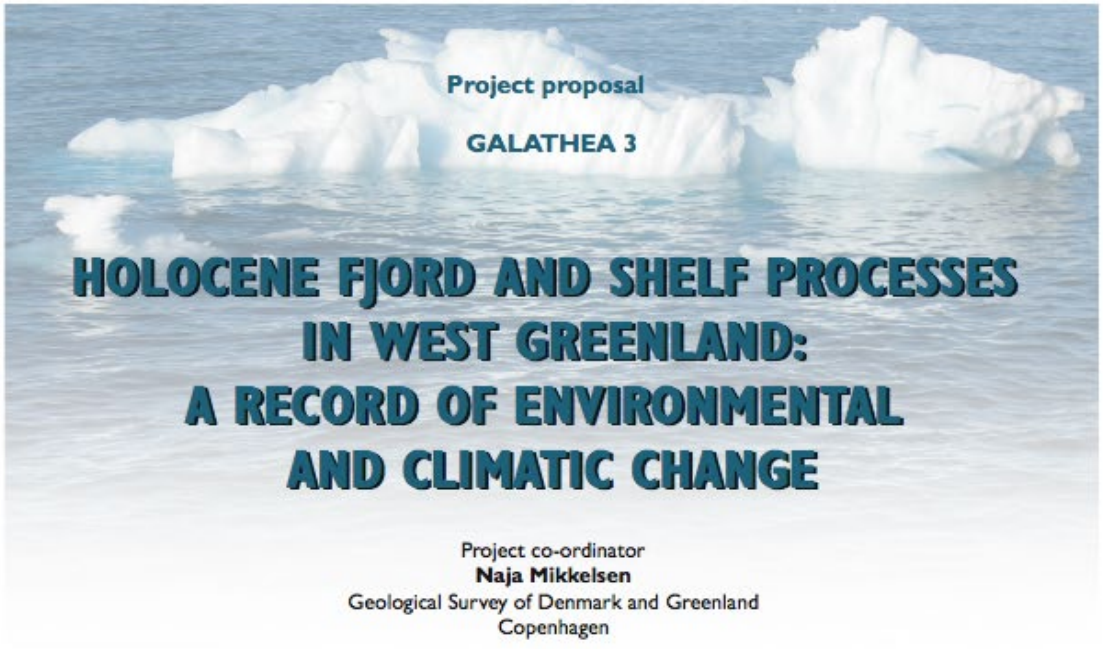


Fig. 15. The project group behind the project *Holocene fjord and shelf processes* onboard the HMSD *Vædderen*. From left to right is: Naja Mikkelsen, Aaju Sofiaraq Simonsen, Jack Schilling, Esajas Arqe, Birger Larsen, Niels Nørgaard-Pedersen, Majken Djurhuus Poulsen and Ole Bennike.



Project proposal

GALATHEA 3

HOLOCENE FJORD AND SHELF PROCESSES IN WEST GREENLAND: A RECORD OF ENVIRONMENTAL AND CLIMATIC CHANGE

Project co-ordinator
Naja Mikkelsen
Geological Survey of Denmark and Greenland
Copenhagen

Minik Rosing
Geological Museum
University of Copenhagen

Antoon Kuijpers & Birger Larsen
Geological Survey of Denmark and Greenland
Copenhagen

Erik Buch
Danish Meterological Institute
Copenhagen

Søren Rysgaard
Pinngortitaleriffik
Nuuk

Claus Andreasen
The Greenland National Museum and Archives
Nuuk

Henrik Fossing
National Environmental Research Institute
Roskilde

B. Grønnow, H.C. Gulløv, J. Arneborg & E.L. Jensen
The National Museum
Copenhagen

Reinhard Møbjerg Kristensen
Zoological Museum
Copenhagen

Holocene fjord and shelf processes in West Greenland:

a record of environmental and climatic change

Purpose

The aim of the project is to obtain new knowledge about changes in Greenland's climate and recent geological history through studies of marine sedimentary sequences. The project focuses on studies of three coastal areas in West Greenland. Based on geological data from seabed cores and data from geophysical studies, Greenland's climatic history and geological development since the last Ice Age will be examined and related to future climate scenarios and climate models. In this connection, the focus will be on the climatic development over the latest 4.500 years in order to elucidate the climatic and environmental changes that have influenced Greenland's population and cultural history since the first Inuit migration to Greenland. In addition to the marine geological studies, a number of other research fields within the natural sciences and the humanities will form part of the project, including biology, oceanography, archaeology and history. It will thus be possible to study the interplay between some of the factors that have influenced climate development, settlement patterns and hydrological circulation in the west Greenland coastal areas since the end of the last glacial period.

Another important goal of the project is to strengthen and further develop research collaboration within the natural sciences and the humanities between Denmark and Greenland. In order to support research education and recruiting in Greenland young Greenland researchers will participate in the cruise and in the subsequent work.

Scientific background

During recent decades, the average temperature in the Arctic has risen more than twice as much as the temperature in the rest of the world, and widespread melting of sea ice has been observed. Climate models predict a pronounced rise in temperature in the Arctic area in the course of this century, with winters becoming shorter and warmer whilst precipitation increases at the same time as the snow and ice cover shrinks. This situation is the result of both known and as yet unproven processes and factors. However, the future climatic scenarios are not unique, as the geological history of the Earth shows both cyclic and chaotic variations in environmental and climatic conditions, which are today recorded in both recent/sub-recent and fossilised marine sediments.

The project will focus on marine geological studies of three areas along Greenland's west coast: southwest Greenland in the Qaqortoq/Julianehåb area, the Godthåb Fjord region and the Disko Bay area. Greenland's climatic and geological history since the end of the Ice Age will be examined on the basis of geological data from sea-floor cores and data from geophysical studies. Studies of 3.8-billion-year-old marine sedimentary rocks will also be included in the project. The purpose of these studies is to compare and contrast these very old sediments with the recent/sub-recent marine sediments.

Holocene climatic variations and previous glaciation of the shelf

The primary scientific focus of the project is directed towards marine geological studies of three fjord and shelf areas in West Greenland. The goal is to establish an overall picture of the differences and similarities in the post-glacial development of these three areas, seen in a geological and climatic perspective. The project thus aims to reconstruct the changes in the circulation patterns in the Greenlandic fjords and shelf areas, and to relate these changes to Holocene climate changes. Special emphasis will be placed on reconstructing the freshwater melting of the Greenland Inland Ice, the extent of sea ice and the occurrence of icebergs off South and West Greenland, as well as the possible relationships and connections with the North Atlantic Thermohaline Circulation system, including the apparent counter-phase between the climatic conditions of South Greenland and Northwestern Europe.

The freshwater balance in polar areas is an important parameter that affects the global climate system, including the conditions in the Labrador Sea and the Davis Strait. Generally, an increase in freshwater inflow will favour the formation of sea ice in the Labrador Sea and lead to a reduction in deep-water convection, which, according to the climate models, may eventually lead to a reduction in the North Atlantic circulation and thus a colder climate in the North Atlantic region. Micropalaeontological studies of marine sediment cores will give a detailed picture of the late Holocene climate changes, including changes in the influence of the dominant North Atlantic Ocean currents. Special focus will be directed towards the West Greenland current system in the coastal areas of West Greenland, storm frequencies and variations in the quantity and occurrence of sea and fjord ice. Extensive valley systems are known to occur on the shelf off the larger fjord and are related to the melting of the Greenland Inland Ice. Using side-scanning sonar studies, selected parts of these valley systems will be surveyed and their origins investigated. The Ilulissat/Jakobshavn Glacier flows into the Disko Bay area, where the outflow of freshwater forms a freshwater plume, while the sea ice formation in winter results in the formation of salt water with high density. During the advances and retreats of the glacier front, the plume has changed position, and these changes will be surveyed. Furthermore, the Egedesminde Trench in the Disko Bay and the large submarine sediment fan flanking the shelf will be studied with a view to determining the mode of formation and the age of these geological structures.

The shelf off the west coast of Greenland displays features indicating that large numbers of icebergs have ground their way across the seabed during times of lowered sea level. The direction and extent of these plough marks will be surveyed using deep-tow sidescan sonar equipment. Studies will be carried out in the Disko Bay area in particular, where large icebergs from the Ilulissat Glacier are believed to have left deep tracks in the seabed; the direction and size of the tracks testify to changes in the direction and strength of the ice flows. Geophysical investigations will also provide information on features such as drowned coastlines, lateral moraines, turbidites and changes in the sea level.

In connection with sampling the seabed using a grab sampler off Ilulissat Icefjord, the sediments' contents of Ice Rafted Detritus (IRD) will be examined. As this material can only originate from ice that has gathered its load from the bedrock, an analysis of the IRD will provide data on the nature of these rocks, which are presently covered by the ice stream.

A distinct Mid-Holocene reflector has previously been observed in the sediment succession off Christianshåb. This reflector can be reached using a piston corer, which will make it possible to date and examine the mode of formation of this distinctive surface.

Glaciology

In recent years, there has been particular focus on changes in the dynamics of ice flows, glaciers and ice shelves. These changes are to a large degree the result of the pronounced melting, retreat and break-up of the ice, a pattern that has been replicated globally within a range of glaciers and icecaps. Pronounced changes in the dynamics of the Inland Ice and the glaciers in Greenland have also been registered, as illustrated by the Ilulissat Glacier. The flow rate of this glacier has almost doubled (to 13 km/year) since 1997. In this connection, the Ilulissat Icefjord and Disko Bay are unique areas of study, as the advances and retreats of the glacier front have been documented in detail since 1850. These glacier front changes are reflected in the distribution of Inuit settlements along the fjord. New model studies show that a possible response by Greenland's ice cap to continued global warming will be an acceleration of the glaciers' speed, displacement of the glaciers' front on to the shelf and an increase in the production of icebergs. To be able to predict the response of the ice cap to global warming, it is necessary to understand the factors that control these movements. It has been shown that changes in the dynamics of a glacier front can quickly propagate upstream and have a pronounced effect on the drawdown of ice, which occurs from the ice cap to the oceans. This increase in the outflow of glacial ice to the oceans influences both the global sea level and the flux of freshwater to the oceans. At Ilulissat, however, it has been shown, that a temperature increase in the area at the start of the 1900s did not influence the location of the glacier front. It is therefore unclear whether this 'insensitivity' was the result of a delay in the climate/ice/ocean system response to the change in temperature, or if the present sudden change is due to completely different factors. To determine possible factors affecting the stability of a glacier, the advances and retreats of the glacier over a longer period of time must be surveyed and put into the context of previous climatic variations, as reflected in sediment cores.

Climate changes, cultural patterns and settlements

Over a short time span, large but long-term climate changes are not immediately seen to influence biological ecosystems and cultures. On the other hand, pronounced short-term climate changes can significantly influence both biological and social systems – especially in Arctic regions, where conditions for life are marginal. Since the first immigration, people in Greenland have lived in coastal and fjord areas – and through history they have been affected by both small and large changes in the marine climate and environment.

Natural science and humanities research is combined in the project in order to relate information about changes in Greenland's cultural history to data concerning climate and environmental changes. The studies will focus on the various waves of Inuit immigration, which have moved along the Greenland coast in the course of the latest 4,500 years, in an attempt to determine whether the different cultures arose and disappeared synchronously with changes in climatic and environmental conditions, or if other factors were involved.

The Norse period, when descendants of European Vikings lived in Greenland from about 1000 to 1500 AD, will also be the subject of a combined natural science-archaeological study. The Norse settled during the warm period in Greenland as farmers in Southwest Greenland and in the Godthåb Fjord region. The settlement in the Godthåb Fjord region was abandoned after 300 years, while the settlement in South Greenland was depopulated by the end of the 1500s. Preliminary studies indicate that the extinction of the Norse settlements can to some extent be connected with climate changes. As part of further investigation into the cause of the disappearance of the Norse, the marine geological studies are supplemented by land-based archaeological observations. These investigations will provide information on the Norse' social strategies in relation to the changes in climate and environment. In the Disko Bay area, the combined geological and archaeological

studies will more closely examine the relationship between the Inuit settlement patterns, the marked changes in sea level and the advances and retreats of the glaciers. In south Greenland, historical documents will be used to investigate the migration of people from the east coast to the west coast of Greenland about 100 years ago and eventually relate this pattern to changes in the social structure and external factors such as climate change.

Marine climatic framework

In association with geological sampling, it is also important to collect physical and chemical oceanographic information with a view to surveying the marine climate conditions under which present sedimentation occurs. This will form the basis for establishing a relationship between present conditions and the information, contained in sediment cores, about climatic conditions of previous ages.

The marine climate in West Greenland is today dominated by atmospheric changes and the inflow of Arctic water via the East Greenland Current and Atlantic water via the Irminger Current. Thus currents, salinity and temperature in West Greenland depend to a large extent on the ocean circulation in the North Atlantic and its variability. As the North Atlantic Oscillation (NAO) has a large influence on both the atmospheric conditions in Greenland and the ocean circulation in the North Atlantic, and thus on the intensity of the inflow of Polar and Irminger water to West Greenland waters, there is a close correlation between NAO and West Greenland's marine climate. The observed counter-phase in air temperature between West Greenland and Northern Europe is well known today and a large part of it is believed to be related to NAO. In the course of the warming that has occurred over large parts of the northern hemisphere in the last decades, however, a smaller cooling in South Greenland and Northeast Canada has been observed; this is too pronounced to be explained by a positive NAO phase alone. Through studies of sediment cores, NAO's phase/counter-phase through time will be examined.

Establishing a relationship between information from sediment cores and the marine climate will therefore contribute to a survey of the change in the West Greenland marine climate over time and indirectly show NAO's variability in previous periods. This will contribute to an increased understanding of Greenland's climate and its effects on marine ecology.

West Greenland's marine biological system

The marine ecosystems of West Greenland are today very productive and form the basis for a large fishing industry. An understanding of the environmental conditions off Greenland's west coast builds on an understanding of the interplay and relationship between the cold East Greenland Current and the warmer Irminger Current. Oceanographic studies of these currents will significantly improve the understanding of this interplay.

Sea ice also plays an important role. Observations of sea ice have shown a marked reduction in both areal extent and thickness in the Arctic Ocean and along Greenland's east coast. The extent of sea ice off Greenland's west coast has also been reduced, although to a lesser extent. Regional climate calculations predict a continued reduction in sea ice cover during this century. In particular, changes in the distribution of sea ice and the contribution of freshwater from land could have a pronounced effect on biological production and transport of carbon within the marine system. Research results from Greenlandic waters have shown that primary production rises as a consequence of a reduction in sea ice cover and consequently increased light for photosynthesis, which has a major influence on all trophic levels. The results will, in the future, contribute to understanding of how the ongoing climate changes affect the distribution, composition and production of marine plants and animals in the Arctic region. These data will be compared with data from sediment cores in order to examine

the development over time. Should the climate and ocean currents change, this can have great consequences for the West Greenland marine ecosystems and thus for the Greenlandic society.

On the basis of detailed studies of a transect from the bottom of Godthåb Fjord to beyond the edge of the shelf, marine biological studies will increase the understanding of the relationship between the biological conditions (e.g. primary production, grazing, decomposition, food-chain structure and species composition) and physical parameters (e.g. climate, snow and sea ice conditions, freshwater inflow, salinity, temperature). In addition, biological studies of the plankton content of the water column will be undertaken and compared with the geological data.

Earliest life and the carbon cycle

After it was formed 4.6 billion years ago, the Earth was subjected to a heavy bombardment by meteorites, which decreased after about 700 million years. This allowed the Earth's crust to stabilise, and just 100 million years later life in the form of plankton had colonised the oceans. Traces of these planktonic organisms are found today as biogenic carbon in the world's oldest rocks at Isua in the Godthåb Fjord region. The exciting aspect of these early organisms is that they might have contributed to reducing the quantity of the greenhouse gas CO_2 in the atmosphere in an early phase of the Earth's geological development, thus helping reduce the Earth's temperature at a time when radiation from the Sun underwent a pronounced increase. It has not yet been determined whether this is the case, but one or more factors must have prevented total evaporation of the early seas and consequent desiccation of the planet. The project will focus on the 3.8-billion-year-old marine metasediments from Isua; geochemical and geological studies will focus on the incipient interplay between the Earth and its living organisms. An international research team will look for signs of microbial decomposition of the seafloor some 3.8 billion years ago. The project will similarly try to determine the origin of water on Earth, and how the water cycle functioned in the early history of the Earth.

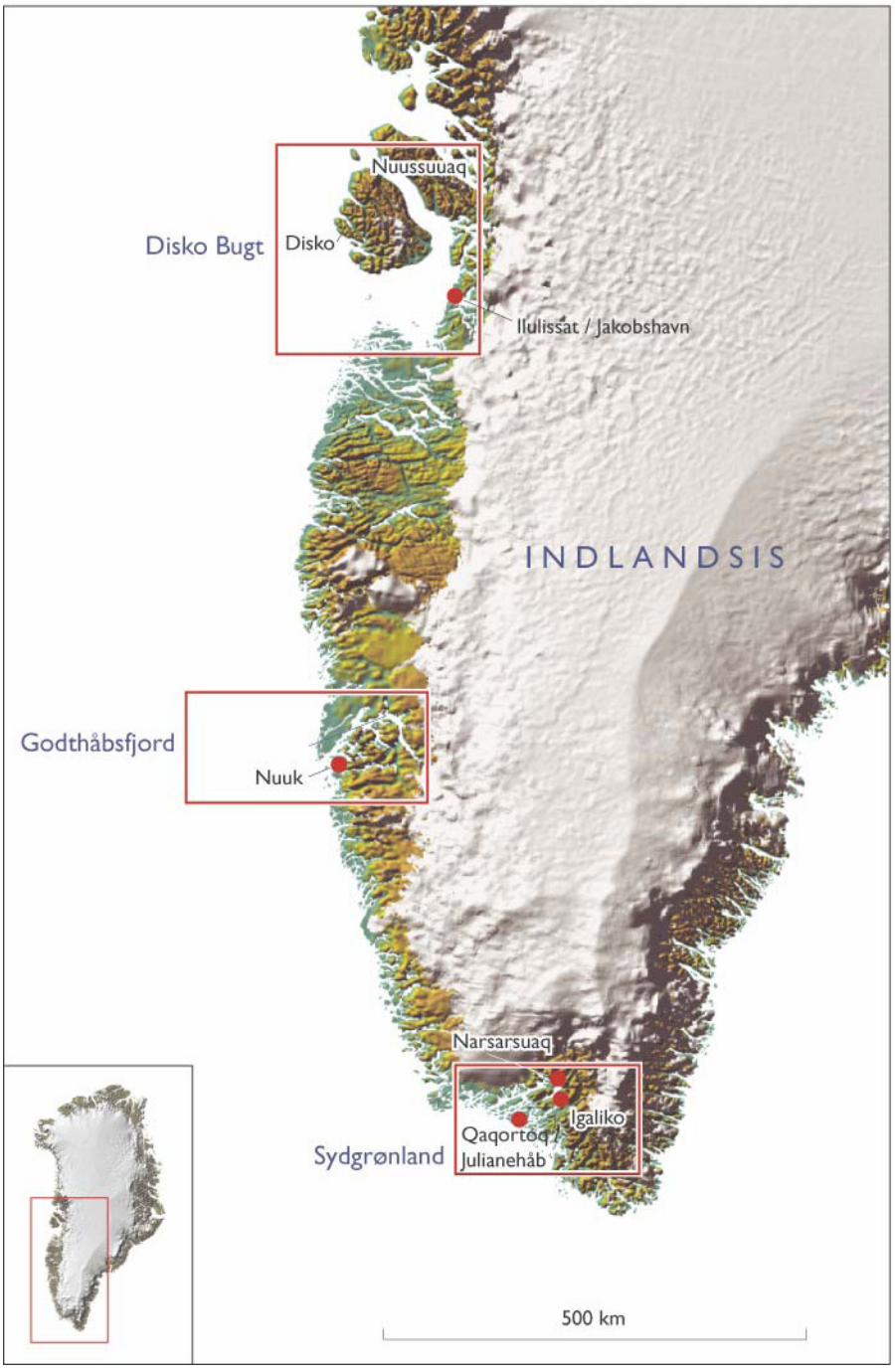
In order to establish a modern analogy to these early sediments found at Isua, Holocene carbon cycles in the West Greenland fjord systems will be studied. At a depth of several metres below the seabed, large quantities of methane gas are produced as a result of the decomposition of organic matter. Methane, like carbon dioxide, is both an important component of the carbon cycle and an important greenhouse gas. There is concern about increased methane release from Arctic areas, since this may be linked to, and result in, increased rates of global warming. In this context, the decomposition of organic material and methane release from the seabed will be examined in the most recent parts of the sediment cores in order to increase our understanding of the carbon cycle in the Arctic marine environment, including the link to present as well as past climate change.

Programme of research

This multidisciplinary scientific research project comprises the following study programmes:
The marine geological programme is based on geophysical, sedimentological, micro-palaeontological and geochemical analyses and AMS C-14 and Pb-210 dating of sediment cores from the following three study areas: South Greenland, the Godthåb Fjord region, and the Disko Bay area. Reflection seismic studies will be carried out in the three areas to document the subsurface geology and to locate suitable sedimentary basins for coring. The sediment cores will be extracted using a gravity corer (6 metre cores) and a piston corer (12 metre cores). In addition, box cores and seabed samples will be taken with a large grab at each site. Deep-tow side-scan sonar studies will be carried out in the valley systems off the large fjord systems, while ROV studies and vibro-coring will be undertaken in Igaliku Fjord to localise and subsequently date drowned beaches.

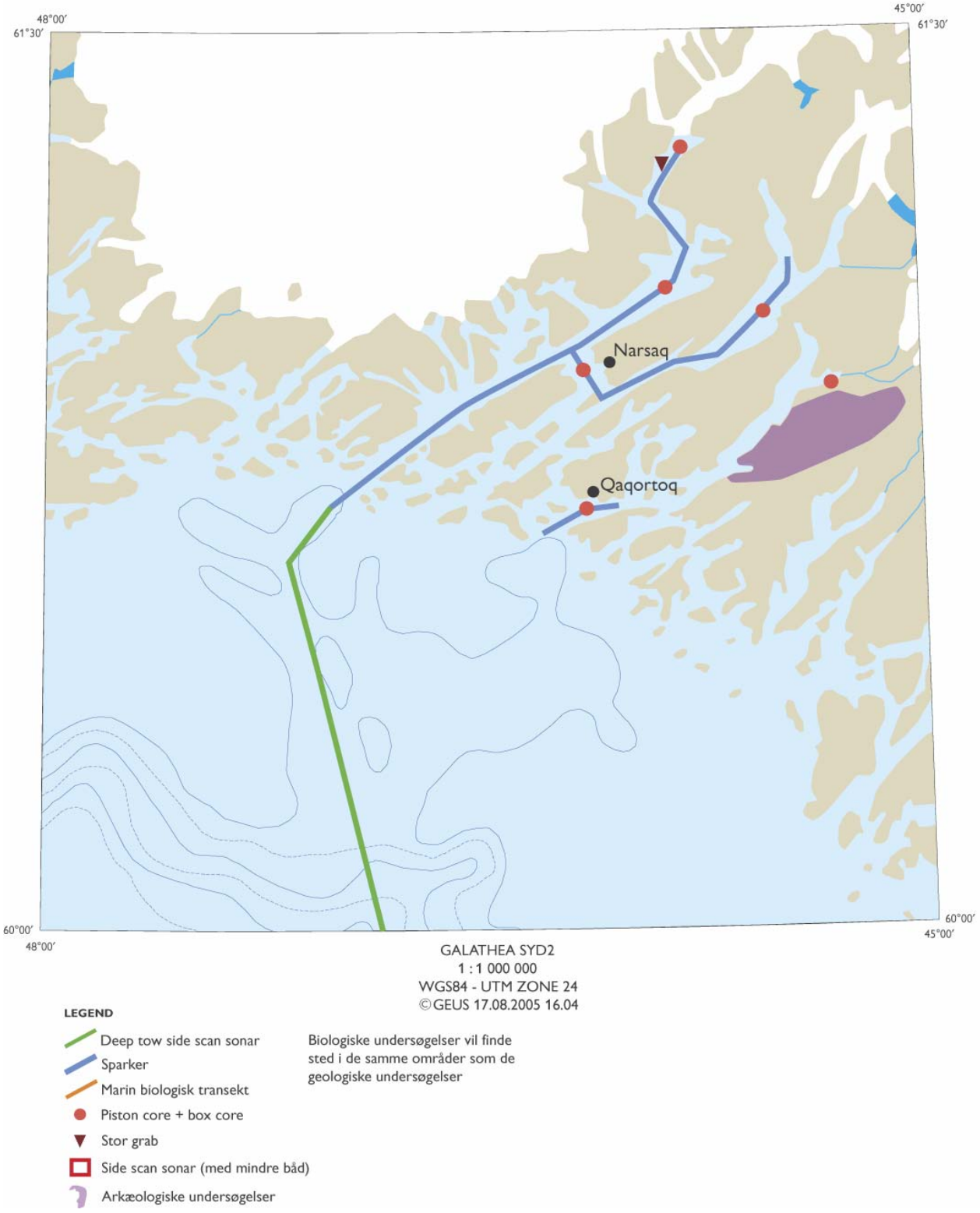
Geological studies on land will include sampling of sedimentary rocks in geological profiles, followed by geochemical and isotope geochemical studies in laboratories.
The marine biological study programme will comprise vertical measurements of salinity, temperature, chlorophyll, nutrients, carbon (DIC/alkalinity), the composition of the most important planktonic components, larvae, shrimps and fish. In a transect in the Godthåb Fjord region, measurements will be taken at the seabed of O_2, carbon (DIC), the exchange of nutrients between the water phase and the seabed and of carbon burial. Conditions for the composition and spread of indicator species among seabed fauna will also be studied. Studies of the planktonic components will be undertaken using Bongo nets with 500 μm and 100 μm mesh, whereas the seabed fauna will be studied using grab samples and box cores.
Oceanographic studies will routinely encompass measurements of temperature, pressure, wind, precipitation, light, PAR & UVB; in addition, sea ice data off the west coast will be acquired from satellites. The oceanographic study programme also comprises a survey of horizontal and vertical temperatures, salinity and oxygen ratio using CTD, including water sampling for calibration of the sensors. Current conditions will also be measured using a ship-mounted ADCP. Surveying nutrient concentrations and other geochemical data will occur in the form of water samples using a rosette sampler coupled to the CTD.
Archaeological and cultural-historical studies will be made on land in the South Greenland area, in order to unravel the mutual relationships between Inuit and Norse settlements; preliminary excavations will be undertaken of selected sites. The study programme in the Disko Bay will encompass studies and surveys of the mutual relationship between Inuit ruins and sea level, and the location of settlements in relation to the movements of the glacier fronts. Historical sources will be included to throw light on the most recent history in south Greenland especially related to the migration from the east coast to the west coast of Greenland.
Schedule: The project is scheduled for 19 days, of which 14 days will be devoted to scientific work and 5 days to transits and port calls.

Bilag 1


Nuussuuaq
Disko Bugt
Disko
Ilulissat / Jakobshavn
INDLANDSIS
Godthåbsfjord
Nuuk
Narsarsuaq
Igaliko
Qaqortoq /
Julianehåb
Sydgrønland
500 km

Bilag 1a

Sydgrønland

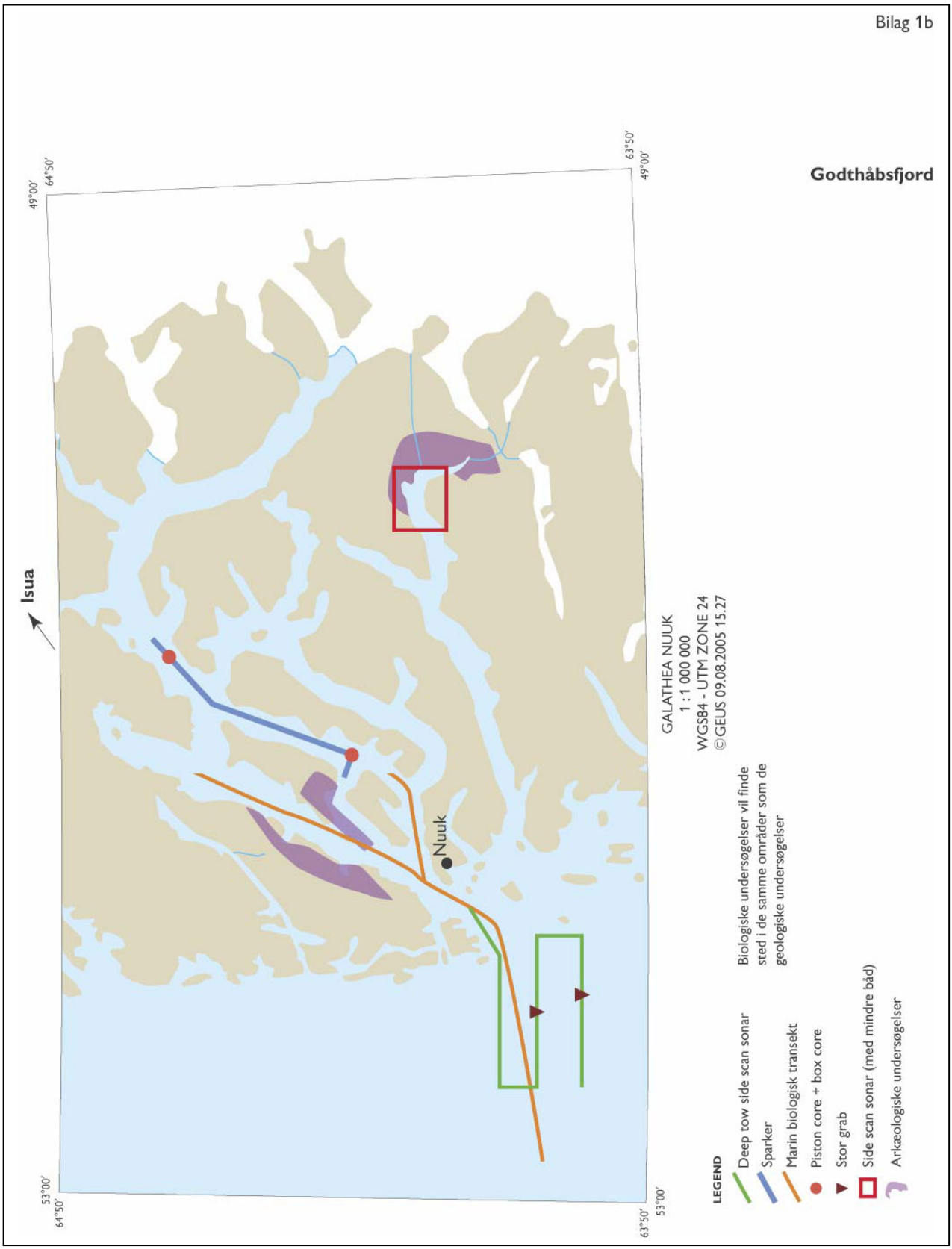


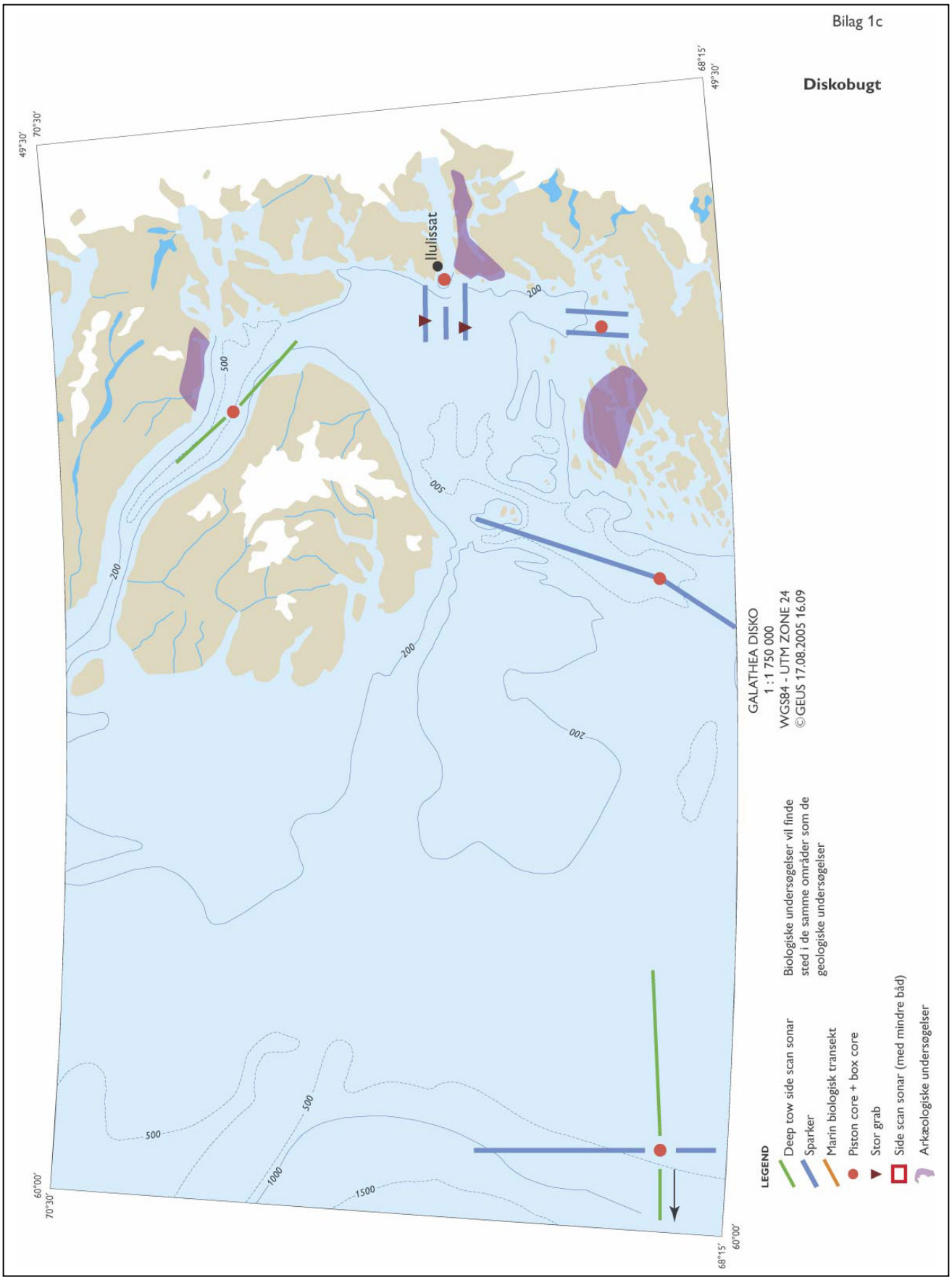
GALATHEA SYD2
1 : 1 000 000
WGS84 - UTM ZONE 24
©GEUS 17.08.2005 16.04

LEGEND

- Deep tow side scan sonar
- Sparker
- Marin biologisk transekt
- Piston core + box core
- Stor grab
- Side scan sonar (med mindre båd)
- Arkæologiske undersøgelser

Biologiske undersøgelser vil finde sted i de samme områder som de geologiske undersøgelser


Bilag 1b
Godthåbsfjord
Isua
Nuuk
49°00'
64°50'
63°50'
53°00'
GALATHEA NUUK
1 : 1 000 000
WGS84 - UTM ZONE 24
©GEUS 09.08.2005 15.27
LEGEND
Deep tow side scan sonar
Sparker
Marin biologisk transekt
Piston core + box core
Stor grab
Side scan sonar (med mindre båd)
Arkæologiske undersøgelser
Biologiske undersøgelser vil finde sted i de samme områder som de geologiske undersøgelser


Bilag 1c
Diskobugt
Ilulissat
200
500
1000
1500
68°15'
49°30'
70°30'
60°00'
GALATHEA DISKO
1 : 1 750 000
WGS84 - UTM ZONE 24
©GEUS 17.08.2005 16.09
Biologiske undersøgelser vil finde sted i de samme områder som de geologiske undersøgelser
LEGEND
Deep tow side scan sonar
Sparker
Marin biologisk transekt
Piston core + box core
Stor grab
Side scan sonar (med mindre båd)
Arkæologiske undersøgelser