GEOLOGY OF GREENLAND SURVEY BULLETIN 189 • 2001

Review of Greenland activities 2000

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

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Edited by
A.K. Higgins and Karsten Secher

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Climatic research, Greenland activities 2000, hyperspectral survey, limnology, marine geophysics, mineral resources, petroleum geology, publications review, sedimentology, stratigraphy.

Cover
The Nalunaq gold prospect, South Greenland, has been in focus in 2000 with test mining for feasibility studies. The scene features the east face of the Nalunaq mountain, the summit of which is 1100 m above the temporary mining camp situated on the valley floor. The winding road provides access to the adit portals at exploration levels 350, 400 and 450 m (see the article on *Nalunaq gold prospect*, page 70). Photo: Hans Christian Langager.

Frontispiece: facing page
Swarm of hydrothermal veins ('Yellow Zone') situated at the margin of a Palaeogene breccia pipe (upper right) north of Amdrup Fjord, southern East Greenland. The person clad in red in the centre of the picture is collecting a chip sample, which returned 0.8% Cu, 1.4% Pb, 3.2% Zn, 0.3 ppm Au and 127 ppm Ag over 4 m. The photograph was taken during *EG 2000* (see Nielsen *et al.*, page 83 and Thomassen & Krebs, page 76) and the investigations demonstrate that the area holds a potential for vein-type gold and silver deposits.
Photo: Bjørn Thomassen.

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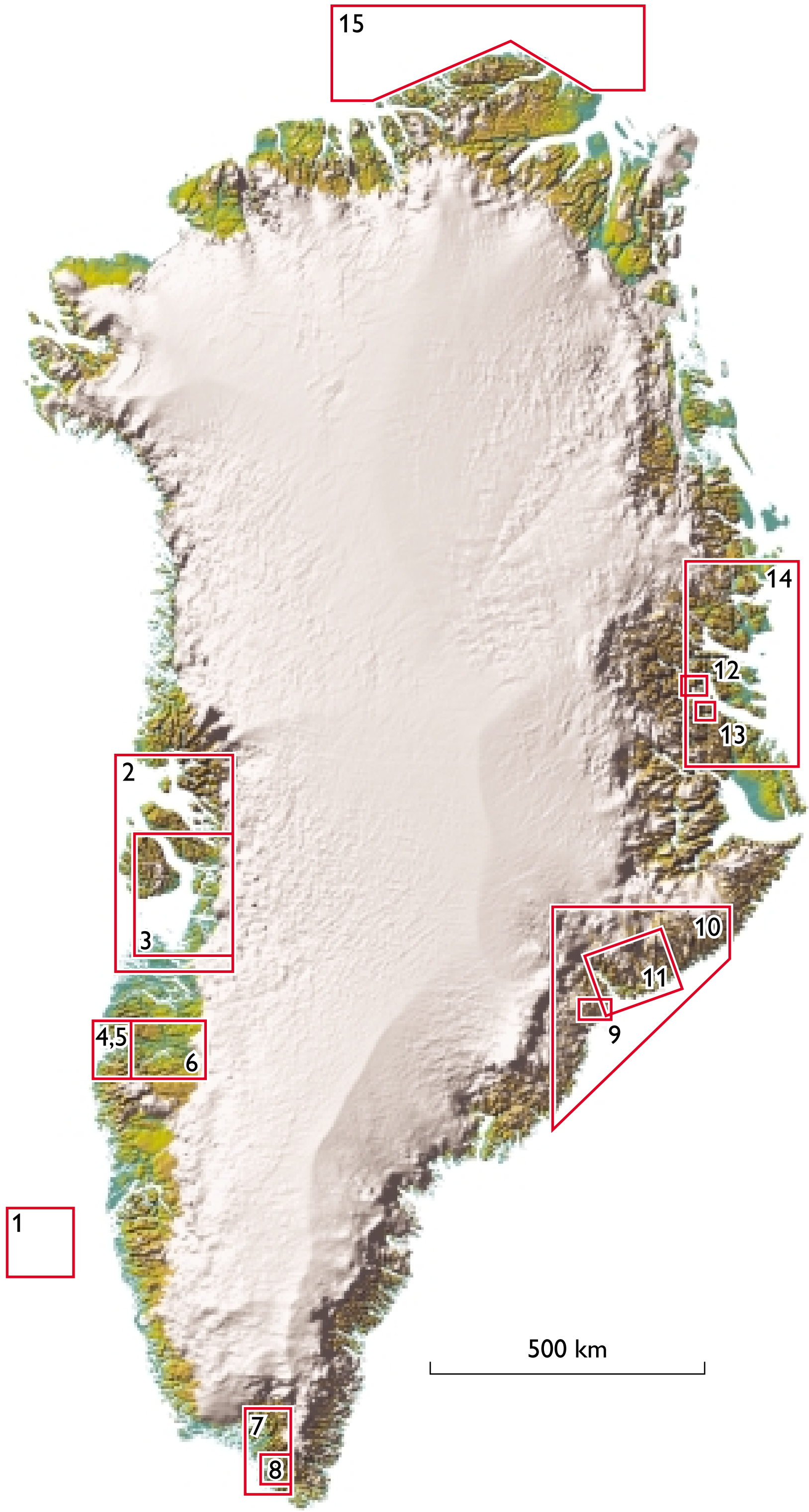


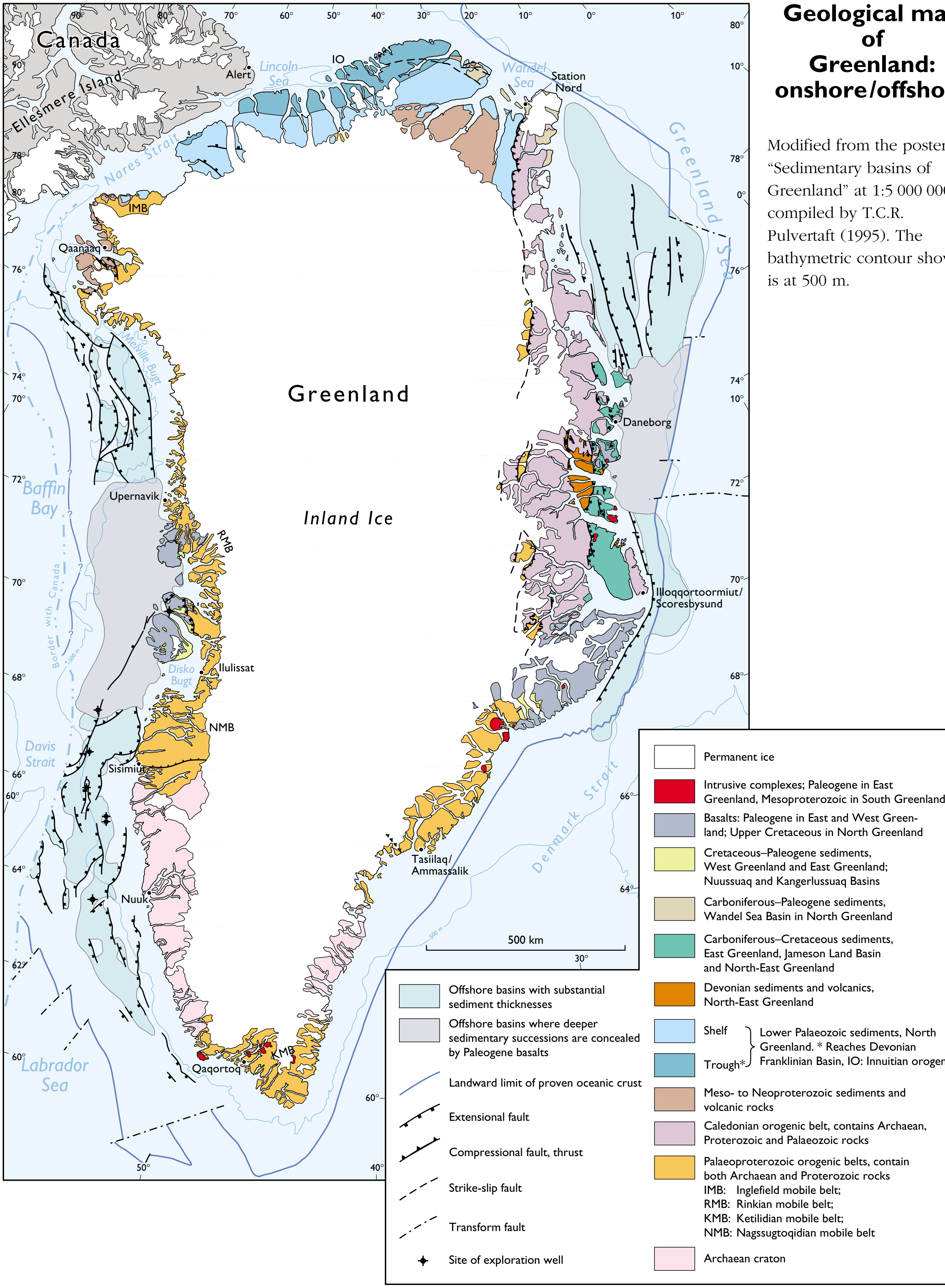
Physiographic map of Greenland showing the locations discussed in the 15 technical papers of this volume. The map is reproduced with courtesy of the National Survey and Cadastre, Copenhagen. For a full list of Survey field activities in 2000 and for the geographical subdivisions as used in this bulletin, see the map in the directorial review (Fig. 1, page 8).

Contents

Numbers of articles correspond to those on to the map opposite

Geological map of Greenland: onshore/offshore

Modified from the poster "Sedimentary basins of Greenland" at 1:5 000 000 compiled by T.C.R. Pulvertaft (1995). The bathymetric contour shown is at 500 m.



The year in focus, 2000

Kai Sørensen
Director

The year 2000 was unusual in that it lacked major field activity directly involved with the systematic geological mapping of Greenland. However, field activities were again many and varied, including a successful high-resolution seismic survey offshore central West Greenland, and a joint Geological Survey of Denmark and Greenland (GEUS) – Danish Lithosphere Centre (DLC) project centred on Kangerlussuaq in southern East Greenland. Of the Survey's 354 personnel, 93 were allocated to Greenland-related activities (Table 1). The Greenland level of activity in 2000, both in Copenhagen and in the field, thus compared favourably with that of 1999.

The Survey is obliged to spend a fixed percentage of its Finance Law grant on Greenland-related activities. These activities are planned each year by the Survey in consultation with the Greenland authorities, in particular the Bureau of Minerals and Petroleum (BMP). The activities, as described in the annual work programme, are approved by the Board of GEUS, on which the BMP is represented. In addition to the Finance Law grant, funding of Greenland activities comes from the BMP, the Danish Energy Research Programme and the Danish National Research Foundation; the last named institution funds the DLC, as well as a number of other research centres in Denmark. Funding for specific research projects in 2000 included grants from the Carlsberg Foundation, the Danish Natural Science Research Council, the Commission for Scientific Research in Greenland and the European Union (EU).

During parts of the year 2000, several geologists from GEUS were seconded to the BMP in Nuuk, Greenland, to assist in work concerning both mineral and oil exploration. Together with BMP, GEUS continues to inform the international oil and mining industries on exploration possibilities in Greenland, both through participation in conferences in Europe and North America, and through publication of the newsletters *Greenland MINEX News* (directed towards the mining industry) and *Ghexis Newsletter* (directed towards the oil industry).

Regional geology and mapping

Field work for the long-term mapping project aimed at the publication of 1:500 000 geological maps of the land areas of Greenland was completed in 1999. One sheet was printed in 2000, and compilation of the final two map sheets in the 14-map series is underway with printing planned for 2001 and 2002 respectively (see also publications review, page 11). Geological maps in the 1:100 000 series continue to be published, currently with about one new sheet annually.

A multinational field party continued studies in the very Early Archaean greenstone belt at Isua, north-east of Nuuk (Fig. 1, **A**). This was planned to be the last year of field activities for the *Isua Multidisciplinary Research*

Table 1. Key statistics on Survey resources

RESOURCES	2000	1999
HUMAN RESOURCES		
Permanent staff (man-years)		
GEUS personnel*	354	356
Allocated to Greenland work	93	87
Greenland field work (persons)		
Total number of participants†	92	85
DLC persons involved	21	27
FINANCIAL RESOURCES (million DKK)		
GEUS Finance Law grant	138	135
Of this spent on Greenland activities	32	33
GEUS external funding‡	77	78
Of this spent on Greenland activities	22	28
DLC spending on Greenland activities	14	18
Total expenditure on Greenland activities	68	79

* excludes DLC staff resource of *c.* 20.
† includes DLC and external scientists.
‡ excludes DLC funds.
From: Annual Accounts 1999/2000 and internal/external sources.

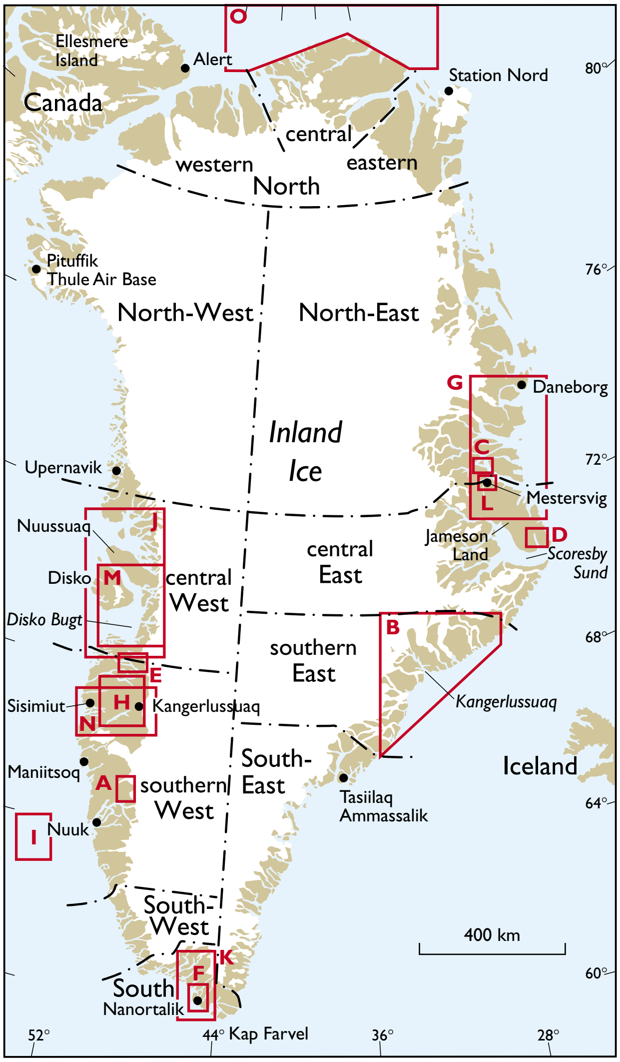


Fig. 1. Map showing the regions in which Survey field activities were carried out in 2000: frames **A–O**. **Letters** underlined below indicate those regions for which articles are presented in this volume; **numbers** 1–15 in parentheses refer to the articles as listed in the Contents and on the adjoining index map (pages 4 and 5).

A: *Isua Multidisciplinary Research Project*, Isukasia region, regional geology and geochronology, early Archaean life.
B: *EG 2000*, Kangerlussuaq area, Cretaceous–Palaeogene sedimentology, investigation of Palaeogene basalt formations and intrusive complexes (9, 10, 11).
C: Ella Ø, Vendian – Lower Ordovician stratigraphy and palaeontology (12).
D: Jameson Land Basin, sedimentological research.
E: *Ussuit 1:100 000 map sheet*, geological mapping.
F: *Nalunaq gold prospect*, Nanortalik area, mining geology and feasibility studies (8).
G: *MINEO* and *HyperGreen* projects, hyperspectral and remote sensing research (14).
H: *Kimberlite Project*, Kangerlussuaq–Sisimiut area, kimberlite survey and exploration.
I: Offshore exploration drilling, Fylla offshore area, drilling of exploration well Qulleq-1 (1).
J: Nuussuaq Basin geophysical survey, high resolution seismics (2).
K: Holocene environment, palaeoclimate studies around former Norse settlements (7).
L: Mestersvig, solifluction and mass-wasting experimental sites revisited (13).
M: Disko Bugt, palaeo-oceanographic research, marine sample coring (3).
N: Søndre Strømfjord, palaeoclimatic research, investigations of lake sediments and airborne pollutants (4, 5, 6).
O: *GRASP* initiatives, North Greenland shelf area, sea-ice observations and satellite data comparison (15).

Project, but due to poor weather conditions field objectives were not met, and field activities will now be carried out in 2001. The management and the Chairman of the Board of GEUS visited Isua during the field season (Fig. 2).

With combined funding from DLC and GEUS, an extensive field programme (*EG 2000*) was carried out in the Kangerlussuaq area of southern East Greenland, from a base at Sødalen close to the Skaergaard intrusion (Fig. 1, **B**). Investigations included studies of the Cretaceous–Palaeogene sedimentary basin, as well as the Palaeogene basalt formations and intrusive complexes. A special grant from the Danish Natural Science Research Council made it possible to retrieve and transport to Copenhagen 6 km of selected drillcore (weighing 20 tons), part of the 80 tons of drillcore recovered during mineral exploration of the Skaergaard intrusion in 1989–1990, and stored in the open at Sødalen. These cores provide an invaluable research archive for an anticipated extensive research programme into differentiation processes in this celebrated layered gabbro intrusion.

Field parties visited North-East and central East Greenland. One party carried out work from a base on Ella Ø (73°N; Fig. 1, **C**), collecting samples and mapping the Lower Palaeozoic carbonate succession which represents the passive margin of the Laurentian continent. A second party based at Constable Pynt (70°45′N; Fig. 1, **D**) investigated the sedimentology and biostratigraphy of the Upper Palaeozoic sediments exposed along the margin of the Jameson Land Basin.

Limited field work was carried out on the Ussuit 1:100 000 map sheet in the Nordre Strømfjord area, southern West Greenland (Fig. 1, **E**).

Fig. 2. Mr. Leo Larsen, Permanent Secretary of the Danish Ministry of Environment and Energy (left) and Dr. Per Buch Andreasen, Chairman of the board of GEUS (right), at Isua north-east of Nuuk in July 2000; some of the visitors to the multinational research group studying the very Early Archaean greenstone belt.
Photo: Johnny Fredericia.

Mineral resources

As part of the southern East Greenland activity reported on above, a field party investigated the mineralisation adjacent to Palaeogene intrusives in the Amdrup Fjord area (68°N; Fig. 1, **B**) and sampled extensively for analytical work.

Survey representatives carried out a courtesy inspection visit to the site of the Nalunaq gold mineralisation (60°N; Fig. 1, **F**) in the Ketilidian supracrustal rocks of South Greenland. In the summer of 2000 the consortium holding the Nalunaq licence carried out test mining as part of a feasibility study with respect to future mining to extract the gold.

The *SUPRASYD* project was concluded with the publication of a CD-ROM with systematic presentations of comprehensive geodata sets collected in the Proterozoic rocks of South Greenland. This is accessible to users in a format allowing GIS-manipulation.

As a part of an EU-funded remote-sensing project (*MINEO*), collection of hyperspectral data was carried out over an area including the abandoned lead-zinc mine at Mestersvig in central East Greenland (Fig. 1, **G**). The project had a double aim of testing the method both for use in environmental monitoring as well as for exploration purposes. Hyperspectral data acquisition in the same region was extended with project *HyperGreen*, a mineral exploration project financed by BMP (Fig. 1, **G**).

Research had also been planned in the kimberlite province to the west of Kangerlussuaq airport in southern West Greenland, but the work accomplished was limited because of logistic problems (Fig. 1, **H**).

Petroleum geology

Drilling of the offshore Qulleq-1 well, some 150 km west of Nuuk, was carried out in the summer of 2000 in the Statoil-operated Fylla licence (Fig. 1, **I**). To the disappointment of all, the well did not encounter hydrocarbons in the tilted fault-block of the Fylla structural complex which it tested. It bottomed out in a reservoir sequence of Santonian age, so that the possible occurrence of Cenomanian–Turonian source rocks in the West Greenland offshore basins remains conjectural.

In preparation for the licensing round planned for late 2001, a comprehensive reassessment of the West Greenland offshore basins has been undertaken, with the aim of identifying potential plays within the area to be included in the licensing round.

In order to obtain a more detailed understanding of the Nuussuaq Basin of central West Greenland, a high-resolution seismic survey was carried out in the waters north and south of the Nuussuaq peninsula using the research vessel R/V *Dana* (Fig. 1, **J**). Data acquisition was carried out over a period of 18 days, with recovery of 2743 line km of high-quality data. Spectacular reservoir sections of Late Cretaceous and Palaeogene age are exposed onshore, and the occurrence of oil seeps in basalts and shows in wells in this basin have demonstrated that the Nuussuaq Basin has exploration potential. The additional seismic data are expected to encourage exploration interest by the petroleum industry.

Below the basalts of southern East Greenland sediments of Cretaceous and Palaeogene age are preserved in the Kangerlussuaq Basin. These sediments provide analogues of interest for exploration on the eastern

Atlantic margin and an important data point in the reconstruction of the regional palaeogeography; a field party from the petroleum industry visited the region during 2000, utilising the field base at Sødalen (Fig. 1, **B**).

General scientific activities

Aspects of the marine and onshore Holocene development of Greenland were in focus in a number of field investigations during the year. Thus, a visit to localities of the former Norse settlements in South Greenland focused on acquisition of palaeoclimatic evidence (Fig. 1, **K**), while a revisit to localities around Mestersvig, central East Greenland (Fig. 1, **L**), established during extensive short-term solifluction studies in the 1950s, permitted long-term conclusions and comparisons.

Following the programme of acquisition of seismic data around Nuussuaq by R/V *Dana,* advantage was taken by marine geologists of GEUS and colleague institutions to use the ship to acquire piston cores, assisted by shallow sub-bottom seismic (chirp) profiling in the Egedesminde Dyb and outside the mouth of Jakobshavn Isfjord, in the Disko Bugt region (Fig. 1, **M**). The cruise constituted a follow-up to the marine geological investigations carried out in 1999 with the smaller research vessel R/V *Porsild*. With R/V *Dana* as a platform it was possible to collect longer cores in the eastern part of Disko Bugt, where sediment accumulation features allow mapping of potential palaeo-oceanographic variations and studies of the dynamic history of the ice margin. Meltwater from the Inland Ice through the Disko Bugt region may have contributed significantly to the deep-water formation in the Labrador Sea.

Palaeolimnological investigations were continued in 2000, with additional sampling and measurements in the water column of inland lakes near Søndre Strømfjord (Fig. 1, **N**); sampling of the lake sediments was also carried out. Palaeoclimate studies are ongoing and measurements of airborne pollutants have been initiated.

In order to investigate the feasibility of establishing data collection from the sea ice to the north of Greenland, observations were made from flights with a C-130 aircraft for comparison with satellite images (Fig. 1, **O**).

Publications

The Survey published four issues in the peer-reviewed *Geology of Greenland Survey Bulletin* series in 2000, as well as a range of other publications including map sheets and compilations of data on CD-ROM. The Survey's 2000 publications dealing with Greenland, including papers published by Survey members and colleagues in international scientific outlets, are reviewed in the following pages (pp. 11–23).

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The year's publications: a review with listing for 2000

Peter R. Dawes
Chief Editor

This review deals with just one part of the Survey's total publication production for the year 2000, namely, that covering geoscientific topics about Greenland, the surrounding oceans and neighbouring lands, i.e. Canada, Svalbard and Iceland. Publications about Denmark, the Faeroe Islands, and other regions of Scandinavia, as well as elsewhere in the world where the Survey has been active, are listed on the Survey's website (www.geus.dk).

Following a summary of the year's achievements, this review lists the publications released in 2000 in the Survey's own series, as well as the scientific and semi-popular articles written by staff and co-workers published in external outlets. International volumes on Greenland and related areas, where staff have acted as scientific editors or compilers, are also cited. Geoscientific abstracts on Greenland, of which about 50 were published during the year, as well as other forms of information transfer (e.g. international symposia, seminars, conferences, posters, etc.) are not listed but may be consulted in the annual publication catalogue that is on the Geological Survey of Denmark and Greenland (GEUS) website.

All available products are listed in the *Catalogue of Greenland publications and data* described below (Fig. 1). The present coverage of Greenland by standard geological maps at scales 1:500 000 and 1:100 000, as well as Quaternary geology and geophysical maps, is shown in the index maps of Fig. 2. The range of products now available on CD-ROM, and released in 2000, is illustrated in Fig. 3 while facsimiles of 2000 covers from four Greenland-relevant publication series are shown in Fig. 4.

Summary of the year's achievements

The Survey's status as a research and advisory institution under the Ministry of Environment and Energy carries a commitment to achieve specific objectives that are outlined and defined in contract periods. The year 2000 was the first year of the new contract period 2000–2003. An assessment in 1999 of the research and publications record of several departments at the Survey (specifically oil- and gas-related research) by an international evaluation panel led to a recommendation for more emphasis on the release of research results in international peer-reviewed publications. Rather than represent a fundamental change in publication strategy, the panel's report (*Danmarks og Grønlands Geologiske Undersøgelse Rapport* 1999/69) calls for a shift in research culture to encourage more staff to publish, or to be involved in the preparation of, high-quality external publications, thus helping to promote the Survey's international profile. In the short life of the present Survey (established in 1995 by the fusion of the former Geological Survey of Denmark and the former Geological Survey of Greenland), the number of scientific research products each year has been dominated by titles released in international outlets. Peer-review bulletins and maps in the Survey's own series have formed only a small part of the total annual publication achievement and this also applies for the year 2000.

The Survey's field operations in Greenland in 2000 and the associated activities in Copenhagen, including those of the Danish Lithosphere Centre (administratively attached to GEUS), resulted in about 50 scientific papers on Greenland and surrounding regions being released in external publication outlets. In addition, three special volumes on Greenland and neighbouring regions published by international journals were edited/compiled by Survey staff.

Maps. The national geological map sheet coverage of Greenland has two scales: 1:500 000 and 1:100 000. The 1:500 000 series that was initiated in the 1970s is nearing completion (see Fig. 2A); the 1:100 000 map series, the first map sheet of which was published in 1967, has a sporadic coverage with the main map-sheet blocks in West, South-West, South and East Greenland (see Fig. 2B). One map sheet from each series was printed in 2000. The publication of the Lambert Land map sheet from North-East Greenland brought the total of 1:500 000 maps released up to 12, leaving just two sheets outstanding. The publication of the map sheet Uiffaq, from the Disko Bugt region of central West Greenland, brings the total of 1:100 000 maps printed up to 55.

The high-resolution, airborne geophysical mapping of West Greenland south of 71°N that was initiated in the early 1990s was completed with a survey in 1999 of the region between 65°40′N and 68°20′N (see Fig. 2D, for magnetic and electromagnetic coverage). In 2000, a total of 62 maps from the 1999 survey were released: two at a scale of 1:250 000 with the remainder at 1:50 000. Parameters available are total magnetic intensity and associated vertical derivatives.

Digital products. The demand for digital versions of all types of geoscientific data is increasing and the Survey is meeting this challenge by releasing soft copies of maps and data on CD-ROM (Fig. 3), as well as improving electronic access to databanks with the aim of delivering information through the internet. In 2000, nine CD-ROMs were issued; some of these comprise compilations of existing data and maps, while others contain new data and refined datasets and images. CD-ROMs designed to give exploration companies easy access to digital multi-datasets were released from onshore South Greenland (mineral potential) and offshore southern West Greenland (hydrocarbon potential).

The South Greenland CD-ROM, that focused on the mineral resource potential of the Palaeoproterozoic Ketilidian mobile belt, contains the hitherto most comprehensive digital assembly of geoscientific data available from a particular region of Greenland, with geological, geophysical, geochemical, topographical, mineral occurrences and remote sensing spatial datasets (see page 15 under *CD-ROM issues*). The West Greenland CD-ROM, specially prepared to highlight the geology and hydrocarbon potential of the offshore region between 63° and 68°N, contains a wide range of geoscientific data, including play types and information on licensing policy and operational conditions. In the *Geology of Denmark and Greenland Map Series,* seven CD-ROMs were released featuring previously published 1:100 000 geological maps bringing the total of digital versions of standard map sheets up to 15 (eight CD-ROMs with geological maps at 1:500 000 have been released previously). Of the 2000 issues, six relate to the Archaean craton of southern West Greenland, and one is from the Palaeoproterozoic Ketilidian mobile belt of South-East Greenland.

Bulletins. Four volumes of the Survey's peer-reviewed series – *Geology of Greenland Survey Bulletin* – were published in 2000. These included the long-awaited descriptive text to the 1:2 500 000 Geological map of Greenland (Bulletin 185); the map sheet itself was printed and released in 1995. A folded copy of the map is included with the bulletin. The map is also available as an individual sheet (96 × 120 cm) supplied in a map roll; an atlas (20 × 24 cm) presenting the map in 12 parts is in preparation. The effort to have the annual *Review of Greenland activities* (Bulletin 186 covering 1999 activities) to the public earlier than usual succeeded with printing in early July 2000. This publication, produced in full colour and with a wide distribution to libraries and the Survey's geological contacts, continues to be the Survey's most popular international publication. The review was followed by a multi-article volume (Bulletin 187) dealing with the sedimentary evolution of the Wandel Sea Basin in North Greenland based on new field work and palynological studies (of some relevance to the hydrocarbon potential of the immediate offshore region), and a volume (Bulletin 188) on the regional tectonic features of the late Phanerozoic rocks of Svartenhuk Halvø, central West Greenland, the origin of which is related to the opening of Baffin Bay.

Ph.D. theses and Reports. The Survey fosters close cooperation with Danish universities and research institutions, and one aspect of this cooperation is the training of students by research scientists and research professors for higher degrees. Five theses on Greenland-related subjects were submitted in 2000 by students based at the Survey as part of Ph.D. degrees at the Universities of Copenhagen and Aarhus. Two of these appeared in the *Danmarks og Grønlands Geologiske Undersøgelse Rapport* series (numbers 2000/64 and 2000/82). In 2000, this open file-type series released 19 reports with a Greenland geological content. Most Greenland-related reports in this series are in English but a few have Danish titles; several reports were issued with data attached in CD-ROM or diskette form.

International newsletters. The two newsletters to international industry – *Ghexis Newsletter and Greenland MINEX News* – continue to gain readership. They are published jointly by GEUS and the Bureau of Minerals and Petroleum (BMP), Government of Greenland, and both newsletters are now available on the websites of both institutions (www.geus.dk and www.bmp.gl; see page 23 under *Availability of Survey publications*). In 2000 there were three issues: numbers 17 and 18 of *Ghexis Newsletter* and number 18 of *Greenland MINEX News*.

Catalogue of Greenland publications and data

The front cover of the catalogue is illustrated in Fig. 1.

Edited by B. Eriksen & P.R. Dawes, 58 pp. Copenhagen: Geological Survey of Denmark and Greenland (revised in September 2000).

The catalogue, available free of charge (see under *Availability of Survey publications* p. 23), contains a complete list of the geoscientific publications on Greenland issued by both the former and present Survey organisations, going back to the first bulletin released by the Geological Survey of Greenland in 1948. Information on 'how to order' with prices and payment details are included. The catalogue also reviews available maps and graphic services (in addition to the geological and geophysical map coverage shown in Fig. 2), including geochemical, topographic, bathymetric and satellite maps at varying scales. A data directory specifying the range of data and services available at the Survey is also included: it comprises various data bases; map, sample and drill-core archives; bibliographic and library facilities, including unpublished maps and reports from the Survey's own activities and those of industry.

The catalogue contains an index to selected topics such as *Fiskenæsset anorthosite and minerals, Glaciology and hydropower, Kimberlites/diatremes, Mineralisation, Offshore geophysics, Onshore geophysics, Palaeontology and stratigraphy, Prospecting, Quaternary and permafrost, Sedimentary and petroleum geology*, as well as an author/project index.

Fig. 1. The front cover of *Catalogue of Greenland publications and data*, 58 pp. For details see the text. The catalogue can be requested free of charge.

Maps

The national geological map sheet coverage at scales 1:500 000 and 1:100 000 is shown in Fig. 2A–C; regions covered by geophysical maps are shown in Fig. 2D.

Standard map sheets (printed in 2000)

Geological map of Greenland, 1:500 000, Lambert Land, sheet 9. Compiled by H.F. Jepsen. Copenhagen: Geological Survey of Denmark and Greenland.

Geological map of Greenland, 1:100 000, Uiffaq 69 V.1 Syd. Compiled by A.K. Pedersen, F. Ulff-Møller, L.M. Larsen, G.K. Pedersen & K.S. Dueholm. Copenhagen: Geological Survey of Denmark and Greenland.

Geology of Denmark and Greenland Map Series CD

This series contains previously published map sheets of the national map coverage and, where available, with accompanying descriptions. The first eight issues feature 1:500 000 map sheets; numbers 9 to 15 released in 2000 are 1:100 000 map sheets. The most recently printed 1:100 000 map sheet available on CD-ROM, Lindenow Fjord CD 15, is illustrated in Fig. 3. The dates in brackets below refer to the printed editions of the original map sheets.

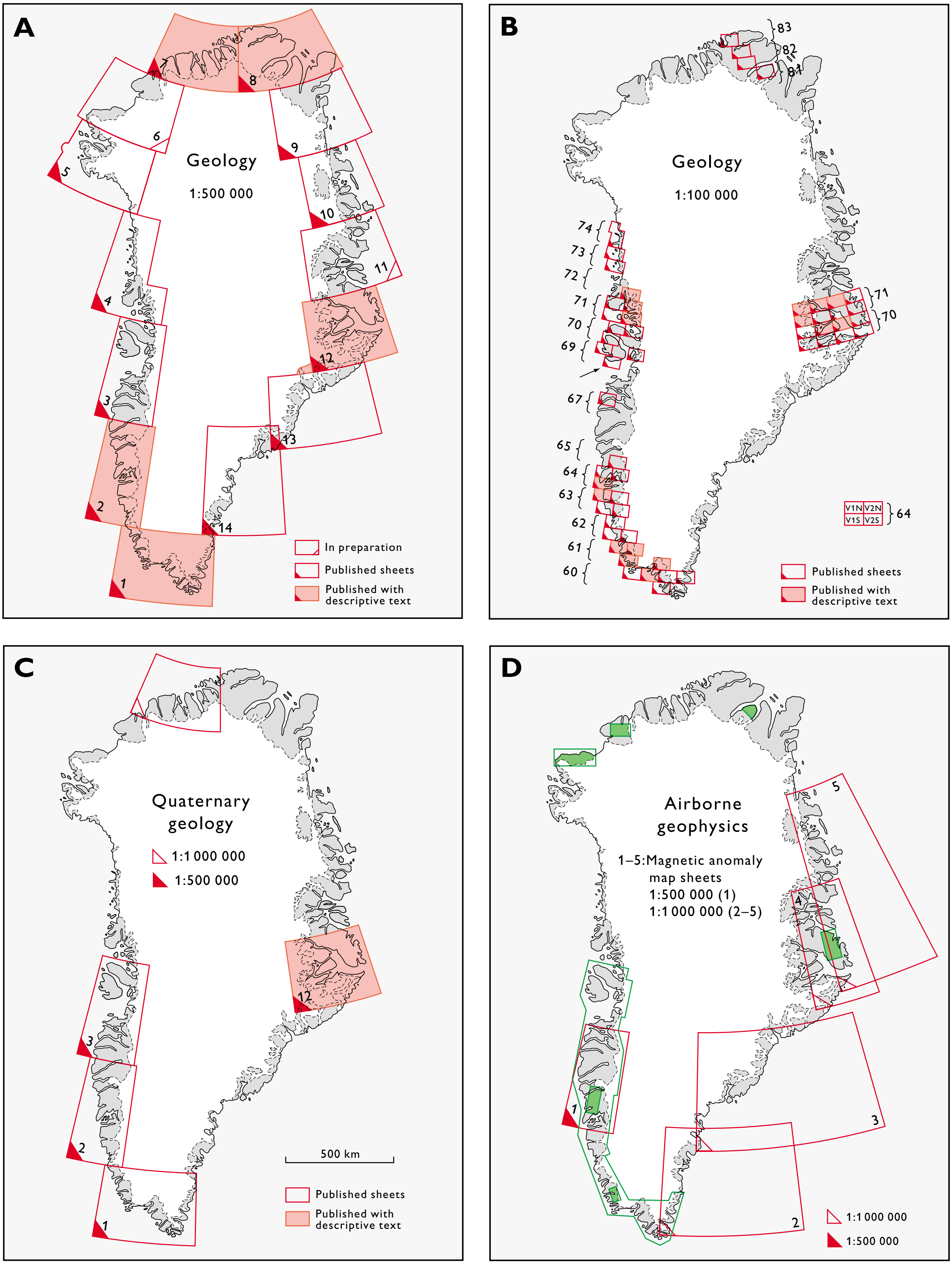
CD 9 Grædefjord, 63 V.1 Syd. (1982)
CD 10 Sinarssuk 63 V.2 Syd. (1980)
CD 11 Kangiata Nuna 63 V.2 Nord. (1981)
CD 12 Fiskefjord 64 V.1 Nord. (1989)
CD 13 Ivisârtoq 64 V.2 Nord. (1988)
CD 14 Isukasia 65 V.2 Nord. (1987)
CD 15 Lindenow Fjord 60 Ø.1 Nord (1998)

Airborne geophysical maps

The regions covered by geophysical maps are shown in Fig. 2D.

Southern West Greenland 65°40′–68°20′N

Sixty-two map sheets were released in 2000: two maps at scale 1:250 000 of total magnetic field intensity (colours and shadow) and first vertical derivative of magnetics, and sixty maps at 1:50 000 of total magnetic field intensity (colours and contours) and first vertical derivative of magnetics. The aeromagnetic survey leading to these


A
Geology
1:500 000
1
2
3
4
5
6
7
8
9
10
11
12
13
14
In preparation
Published sheets
Published with descriptive text
B
Geology
1:100 000
83
82
81
74
73
72
71
70
69
67
65
64
63
62
61
60
71
70
V1N V2N
V1S V2S
64
Published sheets
Published with descriptive text
C
Quaternary geology
1:1 000 000
1:500 000
1
2
3
12
500 km
Published sheets
Published with descriptive text
D
Airborne geophysics
1–5:Magnetic anomaly map sheets
1:500 000 (1)
1:1 000 000 (2–5)
1
2
3
4
5
1:1 000 000
1:500 000

maps (*Aeromag 1999*) was flown in 1999 by Sander Geophysics Ltd., Ottawa, Canada; it was financed by the Bureau of Minerals and Petroleum, Government of Greenland and managed by the Survey.

CD-ROM issues

In addition to the two items listed here, CD-ROMs of map sheets of the national map sheet coverage are featured under *Geology of Denmark and Greenland Map Series CD* above. CD-ROMs with three types of data are illustrated in Fig. 3.

Mineral resource potential of South Greenland: the CD-ROM. *Compiled by* F. Schjøth, A.A. Garde, M.S. Jørgensen, M. Lind, E. Moberg, T.F.D. Nielsen, T.M. Rasmussen, K. Secher, A. Steenfelt, H. Stendal, L. Thorning & T. Tukiainen. The geological province in focus is the Palaeoproterozoic Ketilidian mobile belt. The CD-ROM contains geological, geochemical (stream sediments), geophysical (magnetics, electromagnetics, radiometrics, gravity), topographical, mineral occurrence, mineral exploration and remote sensing spatial datasets presented as maps or images. It is released as part of *Danmarks og Grønlands Geologiske Undersøgelse Rapport* 2000/57; the accompanying report is cited below under that series.

West Greenland 2001 Licensing Round. Nomination 2000/2001. *Compiled by* M. Sønderholm & C. Marcussen. Contains information on West Greenland geology, including prospectivity, play types and source rocks, as well as data types and operational conditions. Prepared by the Survey and available free of charge; also available from BMP (Bureau of Minerals and Petroleum, Greenland) and Nunaoil A/S (national oil and gas company of Greenland).

Facing page
Fig. 2. Geological and geophysical map sheets by the Survey (**red frames**) with regions covered by airborne geophysical surveys 1992–1999 outlined in **green**. Ten sheets (1–5, 7, 8, 12–14) of the 1:500 000 geological coverage are available on CD-ROM in the *Geology of Denmark and Greenland Map Series*. Of the two 1:500 000 sheets yet to be published, sheet 11 is scheduled to be released in 2001. The **arrow** in Fig. 2B marks the Uiffaq map sheet released in 2000. Magnetic maps and data reports are available for all geophysical surveys; in addition, electromagnetic maps and data are available for the six areas with **green shading**.

Fig. 3. Selected CD-ROMs from the year 2000: for details see the listing in the text. **Front** to **back**: *Danmarks og Grønlands Geologiske Undersøgelse Rapport* 2000/57, Mineral resource potential of South Greenland; *Geology of Denmark and Greenland Map Series CD* 15, Geological map of Greenland 1:100 000; West Greenland 2001 Licensing Round, Nomination 2000/2001, available free of charge.

Geology of Greenland Survey Bulletin

This is a peer-reviewed series; an exception is the annual *Review of Greenland activities* which is edited and reviewed internally. Front covers of Bulletins 185, 186 and 188 are illustrated in Fig. 4A–C.

185: Greenland from Archaean to Quaternary. Descriptive text to the Geological map of Greenland, 1:2 500 000. *By* N. Henriksen, A.K. Higgins, F. Kalsbeek & T.C.R. Pulvertaft, 93 pp. + 1 map (see below for summary).

186: Review of Greenland activities 1999. *Edited by* P.R. Dawes & A.K. Higgins, 105 pp. (13 articles, see below for details).

187: Palynology and deposition in the Wandel Sea Basin, eastern North Greenland. *Edited by* L. Stemmerik, 101 pp. (5 articles, see below for summary).

188: The structure of the Cretaceous–Palaeogene sedimentary-volcanic area of Svartenhuk Halvø, central West Greenland. *By* J.G. Larsen & T.C.R. Pulvertaft, 40 pp. + 1 plate with cross-sections (see below for summary).

Bulletin 185: Greenland from Archaean to Quaternary. Descriptive text to the Geological map of Greenland, 1:2 500 000

Greenland's geological development spans a period of 4 Ga from the earliest Archaean to the Quaternary. An

Fig. 4. Selected Survey publications on Greenland from the year 2000: for details see listing in the text. **A–C**: *Geology of Greenland Survey Bulletin* 185, 186 and 188; **D**: *Danmarks og Grønlands Geologiske Undersøgelse Rapport* 2000/9; **E**: *Ghexis Newsletter* No. 18, December 2000; **F**: *Greenland MINEX News* No. 18, February 2000.

overview of the geology was presented in 1995 on the Geological map of Greenland at a scale of 1:2 500 000.

This bulletin provides a description of the geology of Greenland. It is divided into onshore and offshore parts and there are sections on mineral deposits and petroleum potential. It includes an extensive subject index, a place names register and a special legend explanation. The main chapters comprise descriptions of the Precambrian shield with Archaean and Proterozoic crystalline complexes, Proterozoic and Palaeozoic sedimentary basins, Palaeozoic fold belts, late Palaeozoic – Mesozoic sedimentary basins, Tertiary basalts, offshore sedimentary depocentres and the central continental ice sheet – the Inland Ice.

Bulletin 186: Review of Greenland activities 1999

This volume contains a full-page geological map (onshore/offshore), 11 technical articles and two reviews, i.e. a directorial review – The year in focus – and a review of the publications on Greenland and surrounding regions of the North Atlantic released in 1999. The latter includes a listing of publications issued in the Survey's own series and those scientific and semi-popular papers written by its staff and co-workers released in international outlets.

The technical articles report on the main projects carried out in 1999, in all parts of Greenland stretching from 81°N in the north to the southern tip at 60°N. The topics touched on range from geological mapping and stratigraphic studies of Archaean to Quaternary rocks, economic assessments of mineral and petroleum deposits, as well as an airborne geophysical survey in West Greenland. Three papers report on field work dealing with the impact of climatic change on the environment.

The articles

The year in focus, 1999. *By* K. Sørensen, 7–10.

Kane Basin 1999: mapping, stratigraphic studies and economic assessment of Precambrian and Lower Palaeozoic provinces in north-western Greenland. *By* P.R. Dawes, T. Frisch, A.A. Garde, T.R. Iannelli, J.R. Ineson, S.M. Jensen, F. Pirajno, M. Sønderholm, L. Stemmerik, S. Stouge, B. Thomassen & J.A.M. van Gool, 11–28.

Notes on the late Cenozoic history of the Washington Land area, western North Greenland. *By* O. Bennike, 29–34.

A new volcanic province: evidence from glacial erratics in western North Greenland. *By* P.R. Dawes, B. Thomassen & T.I.H. Andersson, 35–41.

Episodic tectono-thermal activity in the southern part of the East Greenland Caledonides. *By* A.G. Leslie & A.P. Nutman, 42–49.

Ketilidian structure and the rapakivi suite between Lindenow Fjord and Kap Farvel, South-East Greenland. *By* B. Chadwick, A.A. Garde, J. Grocott, K.J.W. McCaffrey & M.A. Hamilton, 50–59.

Lake sediment coring in South Greenland in 1999. *By* O. Bennike & S. Björck, 60–64.

Earth's oldest well-preserved mafic dyke swarms in the vicinity of the Isua greenstone belt, southern West Greenland. *By* R.V. White, J.L. Crowley & J.S. Myers, 65–72.

Aeromagnetic survey in southern West Greenland: project Aeromag 1999. *By* T.M. Rasmussen & J.A.M. van Gool, 73–77.

Subfossil insect remains (Chironomidae) and lake-water temperature inference in the Sisimiut–Kangerlussuaq region, southern West Greenland. *By* K.P. Brodersen & N.J. Anderson, 78–82.

Coring of laminated lake sediments for pigment and mineral magnetic analyses, Søndre Strømfjord, southern West Greenland. *By* N.J. Anderson, A. Clarke, R.K. Juhler, S. McGowan & I. Renberg, 83–87.

Petroleum geological activities in West Greenland in 1999. *By* F.G. Christiansen, F. Dalhoff, J.A. Bojesen-Koefoed, J.A. Chalmers, G. Dam, C. Marcussen, H. Nøhr-Hansen, T. Nielsen, A.K. Pedersen, R. Riisager & M. Sønderholm 88–96.

Greenland publications review with listing for 1999. *By* P.R. Dawes & E.W. Glendal, 97–105.

Bulletin 187: Palynology and deposition in the Wandel Sea Basin, eastern North Greenland

The Wandel Sea Basin developed during the Late Palaeozoic to Palaeogene. Two main tectonic epochs of basin evolution are recognised: Late Palaeozoic to Early Triassic block faulting affected the entire basin whereas Mesozoic strike-slip movements affected only the northern part. This is reflected in different thermal histories and hydrocarbon potential.

This bulletin contains five articles based on field and palynological studies. The tectono-stratigraphic history of the south-eastern part of the basin is discussed with implications for shelf areas: a refined, upper age constraint for the compressional tectonism has been gained from detailed study of the Palaeogene microflora. The Early Carboniferous age of the oldest sediments is based on a microflora comparable to that of western Europe, whereas a Late Carboniferous algal flora shows affinities with the Sverdrup Basin flora of Arctic Canada.

Bulletin 188: The structure of the Cretaceous–Palaeogene sedimentary-volcanic area of Svartenhuk Halvø, central West Greenland

Svartenhuk Halvø is a peninsula lying at the northern end of the West Greenland Palaeogene volcanic province. In the down-faulted south-western part of the peninsula upper Paleocene basalts overlie Cretaceous – lower Paleocene sediments, whereas to the north-west the basalts lie directly on Precambrian basement.

This bulletin describes the structural pattern in the basin area. This is dominated by NW–SE-trending extensional faults with downthrow to the north-east. Also trending NW–SE are faulted monoclinal flexure zones that were probably generated by reactivation of deep basement faults. Both the extensional fault arrays and the flexure zones are offset at approximately E–W-trending transfer faults. The regional extension is believed to be related to the opening of Baffin Bay during the late Paleocene – Eocene.

Danmarks og Grønlands Geologiske Undersøgelse Rapport

This open file-type series comprises *unedited* reports in limited numbers covering Greenland, Danish and international topics. The series includes confidential reports, some of which are released when confidentiality expires. Only unclassified numbers dealing with Greenland geological topics are included below. The front cover of Rapport **2000/9** is illustrated in Fig. 4D.

2000/5: GREENMIN. Introduction and users' manual. *By* L. Thorning, L.A. Christensen, M. Lind, H. Stendal & T. Tukiainen, 87 pp. (GREENMIN is the abbreviation for Greenland Mineralisation Data Bank.)

2000/9: Gold indications in northern Inglefield Land, North-West Greenland: a preliminary report from project Kane Basin 1999. *By* B. Thomassen, P.R. Dawes, T.R. Iannelli & F. Pirajno, 14 pp.

2000/13: Indledende lokalisering af grønlandske gletschere med is/vand egnet til export. *By* C.E. Bøggild, A. Weidick & O.B. Olesen, 30 pp. (Danish version of Rapport **2000/73**.)

2000/26: Sammenstilling af sedimentologiske og biostratigrafiske data fra Nuussuaq Bassinet, Vestgrønland. *By* G. Dam, 37 pp. + app.

2000/29: Greenland and the Danish sector – Well data and geophysical data. Prices and sales conditions. 14 pp.

2000/31: Well data summary sheets. Volume 35, released wells from West Greenland. 63 pp.

2000/50: Mineral resource potential of South Greenland: review of new digital data sets. *By* A. Steenfelt, T.F.D. Nielsen & H. Stendal, 47 pp.

2000/56: Cretaceous–Paleocene depositional evolution of the Nuussuaq Basin, West Greenland. Field trip guide prepared for TGS-NOPEC, Nuussuaq–Disko, 19–26 July 2000. *By* G. Dam, 21 pp. + app.

2000/57: Mineral resource potential of South Greenland: the CD-ROM. *By* F. Schjøth, A.A. Garde, M.S. Jørgensen, M. Lind, E. Moberg, T.F.D. Nielsen, T.M. Rasmussen, K. Secher, A. Steenfelt, H. Stendal, L. Thorning & T. Tukiainen, 36 pp. + CD-ROM. (See also above under *CD-ROM issues*.)

2000/60: Bjergkædedannelse i den sydlige del af det kaledoniske foldebælte i Østgrønland – et studie af præorogene basementkomplekser, overliggende sedimentbassiner, synorogene deformationer og overskydninger samt synsenorogene kaledoniske granitintrusioner. *By* N. Henriksen, 148 pp.

2000/64: Geochronology of the pre-Caledonian basement in East Greenland 72°–75°N. *By* K. Thrane, 196 pp. (Cited below under *Ph.D. theses*.)

2000/67: Undersøgelse af bakterielle kimtal i Grønlands indlandsis. *By* C.S. Jacobsen, 10 pp.

2000/72: Sen palæozoisk palæoklima og palæogeografi i det nordatlantiske område. Statusrapport. *By* L. Stemmerik, 8 pp.

2000/73: Preliminary localization of Greenlandic glaciers with ice/water suitable for export. *By* C.E. Bøggild, A. Weidick & O.B. Olesen, 28 pp. (English version of Rapport **2000/13**.)

2000/77: Amdrup Fjord, South-East Greenland: reconnaissance for noble metals. *By* B. Thomassen, 10 pp.

2000/82: Inversion of airborne transient electromagnetic data. *By* L.H. Poulsen, 143 pp. (Cited below under *Ph.D. theses*.)

2000/83: Qulleq-1 (6354/4-1): petroleum geochemistry. Service report prepared for Statoil a.s. *By* J.A. Bojesen-Koefoed, H.P. Nytoft & P. Rosenberg, 35 pp.

2000/88: Tectonic architecture of the East Greenland Caledonides 72°–74°30′N. *By* S. Elvevold, J.C. Escher, K.S. Frederiksen, J.D. Friderichsen, J.A. Gilotti, N. Henriksen, A.K. Higgins, H.F. Jepsen, K.A. Jones, F. Kalsbeek, P.D. Kinny, A.G. Leslie, S. Robertson, M.P. Smith, K. Thrane, & G.R. Watt, 34 pp.

2000/100: Economic investigations in Inglefield Land, North-West Greenland: part of the project Kane Basin 1999. *By* B. Thomassen, F. Pirajno, T.R. Iannelli, P.R. Dawes & S.M. Jensen, 98 pp. + 2 maps, 1 diskette with Tables 1–6.

2000/101: Biostratigraphy of well 6354/4-1 (Qulleq-1), West Greenland. *By* H. Nøhr-Hansen, S. Piasecki, J.A. Rasmussen & E. Sheldon, 81 pp.

2000/104: Assessing and monitoring the environmental impact of mining activities in Europe using advanced Earth Observation techniques. *By* T. Tukiainen, 24 pp. (Includes work in East Greenland.)

Ph.D. theses

In 2000 Ph.D. theses were produced both as reports in the *Danmarks og Grønlands Geologiske Undersøgelse Rapport* series and as unnumbered volumes.

Frederiksen, K.S. 2000: A Neoproterozoic carbonate ramp and base-of-slope succession, the Andrée Land Group, Eleonore Bay Supergroup, North-East Greenland: sedimentary facies, stratigraphy and basin evolution, 242 pp. University of Copenhagen and Geological Survey of Denmark and Greenland, Copenhagen, Denmark. Thesis for Ph.D. degree from the University of Copenhagen.

Kragh, K. 2000: The Citronen Fjord sedimentary exhalative sulphide deposit, North Greenland. A study of primary and diagenetic textures, oxygen and carbon isotopes, and fluid inclusions, 277 pp. Geological Survey of Denmark and Greenland, Copenhagen, Denmark. Thesis for Ph.D. degree from Aarhus University.

Poulsen, L.H. 2000: Inversion of airborne transient electromagnetic data. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2000/82**, 143 pp. Thesis for Ph.D. degree from Aarhus University.

Therkelsen, J. 2000: Petrographic and diagenetic studies on Triassic and Jurassic sandstones in the Traill Ø region, East Greenland, 188 pp. University of Copenhagen and Geological Survey of Denmark and Greenland, Copenhagen, Denmark. Thesis for Ph.D. degree from the University of Copenhagen.

Thrane, K. 2000: Geochronology of the pre-Caledonian basement in East Greenland 72°–75°N. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2000/64**, 196 pp. Thesis for Ph.D. degree from the University of Copenhagen.

Ghexis Newsletter

Greenland hydrocarbon exploration information service. Page 1 of issue No. 18 is illustrated in Fig. 4E.

Issue No. 17, April 2000, 8 pp.
Selected titles:
The first well offshore West Greenland in the new millennium.
New seismic data acquisition in the Nuussuaq Basin during summer 2000.
East Greenland – analogues for the future.
Upper Palaeozoic carbonates in northern Greenland – an analogue to the Barents Sea sucession.
Lower Cretaceous fault-crest sandstones, Hold with Hope – an overlooked play offshore Norway?

Issue No. 18, December 2000, 8 pp.
Selected titles:
Qulleq-1 and the media: myths and facts about the Fylla exploration well.
Invitation to nominate blocks on the West Greenland continental shelf announced.
Seismic acquisition during summer 2000 – the Canadian connection.
Environmental oil spill sensitivity atlas for South-West Greenland.

Greenland MINEX News

Greenland mineral exploration newsletter. Page 1 of issue No. 18 is illustrated in Fig. 4F.

Issue No. 18, February 2000, 8 pp.
Leading article: Exploration commitments for 2000 reduced by 50%.
Selected titles:
Commercial exploration round-up: 2000 update.
Airborne geophysical survey in 1999: Project Aeromag 1999.
High-resolution hyperspectral image data from West and East Greenland.
Palladium potential of Skærgaard: economically viable?

Scientific publications on Greenland and adjoining regions in external outlets

Included here are authored articles as well as edited and compiled volumes by Survey staff. The articles are of four types: (1) from peer-reviewed international journals, (2) from invited special thematic volumes, (3) from conference proceedings, and (4) from other international series. Articles written by staff of the Danish Lithosphere Centre, Copenhagen (administratively attached to the Survey), as well as non-survey staff where the basic work was initiated under the Survey's auspices, are included.

Edited and compiled volumes

Chalmers, J.A. & Cloetingh, S. (eds) 2000: Neogene uplift and tectonics around the North Atlantic. Global and Planetary Change **24**(3–4), 164–318.

Stemmerik, L. & Trappe, J. (eds) 2000: Pangea: the Late Carboniferous to Late Triassic interval. Palaeogeography, Palaeoclimatology, Palaeoecology **161**(1–2), 293 pp.

Stendal, H. (compiler) 2000: Exploration in Greenland: discoveries of the 1990s. Transactions of the Institution of Mining and Metallurgy, section B, Applied earth science **109**(January–April), 66 pp.

Authored articles

Appel, P.W.U. 2000: Gahnite in the ~3.75 Ga Isua Greenstone Belt, West Greenland. Mineralogical Magazine **64**(1), 121–124.

Appel, P.W.U., Bliss, I.C., Coller, D.W., Grahl-Madsen, L. & Petersen, J.S. 2000: Recent gold discoveries in Archaean rocks of central West Greenland. In: Stendal, H. (compiler): Exploration in Greenland: discoveries of the 1990s. Transactions of the Institution of Mining and Metallurgy, section B, Applied earth science **109**(January–April), B34–B41.

Bennike, O. 2000: Palaeoecological studies of Holocene lake sediments from west Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology **155**(3–4), 285–304.

Bennike, O. & Jepsen, H.F. 2000: A new interglacial sequence from Washington Land, northern Greenland. Polar Record **19**(2), 267–270.

Bennike, O., Björck, S., Böcher, J. & Walker, I.R. 2000: The Quaternary arthropod fauna of Greenland: a review with new data. Bulletin of the Geological Society of Denmark **47**(2), 111–134.

Bernstein, S. & Bird, D.K. 2000: Formation of wehrlites through dehydration of metabasalt xenoliths in layered gabbros of the Noe-Nygaard intrusion, SE Greenland. Geological Magazine **137**(2), 109–128.

Bernstein, S., Leslie, A.G., Higgins, A.K. & Brooks, C.K. 2000: Tertiary alkaline volcanics of the Nunatak Region, Northeast Greenland: new observations and comparison with Siberian maymechites. Lithos **53**(1), 1–20.

Breddam, K., Kurz, M.D. & Storey, M. 2000: Mapping out the conduit of the Iceland mantle plume with helium isotopes. Earth and Planetary Science Letters **176**(1), 45–55.

Chalmers, J.A. 2000: Offshore evidence for Neogene uplift in central West Greenland. In: Chalmers, J.A. & Cloetingh, S. (eds): Neogene uplift and tectonics around the North Atlantic. Global and Planetary Change **24**(3–4), 311–318.

Chalmers, J.A., Hamann, N.E., Sønderholm, M. & Olsen, J.C. 2000: West Greenland offshore geology, seeps resemble North Sea prospects. Offshore **60**(10), p. 56 (cont.), p. 58 (cont.), p. 128.

Connelly, J.N. & Mengel, F.C. 2000: Evolution of Archean components in the Paleoproterozoic Nagssugtoqidian Orogen, West Greenland. Geological Society of America Bulletin **112**(5), 747–763.

Connelly, J.N., van Gool, J.A.M. & Mengel, F.C. 2000: Temporal evolution of a deeply eroded orogen: the Nagssugtoqidian Orogen, West Greenland. Canadian Journal of Earth Sciences **37**(8), 1121–1142.

Dam, G., Nøhr-Hansen, H., Pedersen, G.K. & Sønderholm, M. 2000: Sedimentary structural evidence of a new early Campanian rift phase in the Nuussuaq Basin, West Greenland. Cretaceous Research **21**(1), 127–154.

Elvevold, S. & Gilotti, J.A. 2000: Pressure–temperature evolution of retrogressed kyanite eclogites, Weinschenk Island, North-East Greenland Caledonides. Lithos **53**(2), 127–147.

Fitton, J.G., Larsen, L.M., Saunders, A.D., Hardarson, B.S. & Kempton, P.D. 2000: Palaeogene continental to oceanic magmatism on the SE Greenland continental margin at 63°N: a review of the results of Ocean Drilling Program legs 152 and 163. Journal of Petrology **41**(7), 951–966.

Frederiksen, K.S. 2000: Evolution of a Late Proterozoic carbonate ramp (Ymer Ø and Andrée Land Groups, Eleonore Bay Supergroup, East Greenland): response to relative sea-level rise. In: Roland, N.W. & Tessensohn, F. (eds): ICAM III. Third international conference on Arctic margins. Polarforschung **68**, 125–130.

Funck, T., Louden, K.E. & Reid, I.D. 2000: Wide-angle seismic imaging of a Mesoproterozoic anorthosite complex: the Nain Plutonic Suite in Labrador, Canada. Journal of Geophysical Research **105**(B11), 25,693–25,707.

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Garde, A.A., Friend, C.R.L., Nutman, A.P. & Marker, M. 2000: Rapid maturation and stabilisation of middle Archaean continental crust: the Akia terrane, southern West Greenland. Bulletin of the Geological Society of Denmark **47**(1), 1–27.

Grocott, J., Garde A.A., Chadwick, B., Cruden, A.R. & Swager C.[P.] 2000: Reply to Hutton, D.H.W. & Brown, P.E. 2000: Discussion on emplacement of rapakivi granite and syenite by floor depression and roof uplift in the Palaeoproterozoic Ketilidian orogen, South Greenland. Journal of the Geological Society (London) **157**(3), 703–704.

Hald, N. & Tegner, C. 2000: Composition and age of Tertiary sills and dykes, Jameson Land Basin, East Greenland: relation to regional flood volcanism. Lithos **54**(3–4), 207–233.

Hansen, H. & Grönvold, K. 2000: Plagioclase ultraphyric basalts in Iceland: the mush of the rift. Journal of Volcanology and Geothermal Research **98**(1–4), 1–32.

Henriksen, N. & Higgins, A.K. 2000: Early Palaeozoic basin development of North Greenland – part of the Franklinian Basin. In: Roland, N.W. & Tessensohn, F. (eds): ICAM III. Third international conference on Arctic margins. Polarforschung **68**, 131–140.

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Linthout, K., Troelstra, S.R. & Kuijpers, A. 2000: Provenance of coarse ice-rafted detritus near the SE Greenland margin. Geologie en Mijnbouw **79**(1), 109–121.

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Availability of Survey publications

Survey publications can be obtained by contacting the Survey's headquarters in Copenhagen or the Survey's book agent, Geografforlaget ApS, at the addresses given on page 2 of this volume. Of the publications listed in this review, the newsletters to the international mining and oil industries, i.e. *Ghexis Newsletter* and *Greenland MINEX News*, respectively, the *Catalogue of Greenland publications and data* described above, as well as the CD-ROM *The West Greenland 2001 Licensing Round* (see above under *CD-ROM issues*), can be requested from the Survey free of charge.

All Survey publications can be viewed at GEUS headquarters in Copenhagen, Denmark; publications on Greenland are also available at the Bureau of Minerals and Petroleum (BMP) in Nuuk, Greenland. Information on publications and data from Greenland can be found on the Survey's website (www.geus.dk) as well as that of BMP (www.bmp.gl). Several publication series are available on the website, for example the annual *Review of Greenland activities* (this volume), as are the abstracts of volumes in the scientific series *Geology of Greenland Survey Bulletin*, as well as the two newsletters *Ghexis Newsletter* and *Greenland MINEX News*. For details of all Survey publications on Greenland, see the printed *Catalogue of Greenland publications and data* (Fig. 1).

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Petroleum geological activities in West Greenland in 2000

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The summer of 2000 was exciting for everyone interested in the petroleum geology and exploration of West Greenland. The first offshore well in more than 20 years was drilled by the Statoil group in the Fylla licence area, and seismic acquisition activity offshore West Greenland was more intense than previous years with four new surveys being carried out (Fig. 1).

Expectations were high when drilling of the Qulleq-1 well was initiated in July 2000, not only with the licensees and the authorities, but also with the public. The well was classified as highly confidential, but nevertheless all information available was closely followed by the press, especially in Greenland and Denmark, but also internationally (see Ghexis 2000). Disappointment was equally high when the press release in September 2000 reported that the well was dry. Since that time much technical work has been carried out by Statoil and its consultants (Pegrum *et al.* 2001) and by the Geological Survey of Denmark and Greenland (GEUS), and a more balanced view of the positive and negative surprises from the well can now be presented.

When the licence was granted in December 1996, the Fylla licence area consisted of two sub-areas totalling 9487 km^2. Recently the Statoil group relinquished the eastern sub-area, which covers 2645 km^2, after having fulfilled their exploration obligations (Fig. 1). As a consequence, all data within the eastern sub-area are now 'open file' and available from GEUS. The relinquished eastern sub-area is included in the forthcoming licensing round, which has a planned closing date in early 2002.

Although the Qulleq-1 well did not discover hydrocarbons, it has produced new information important to the evaluation of the petroleum exploration potential of offshore West Greenland. With a licensing round in prospect and the several seismic surveys carried out in the summer of 2000 providing many new and interesting exploration targets, Greenland is prepared for continued exploration on a sound geological background, despite the temporary setback from the disappointing outcome of Qulleq-1.

Table 1. Well data for Qulleq-1 (6354/4-1)

Operator:	Statoil A/S
Drill ship:	West Navion
Well name:	6354/4-1 (Qulleq-1)
Co-ordinates:	63°48'48.03" N, 54°27'06.61" W
UTM co-ordinates:	E 625442, N 7078718; Zone 21; central meridian 57°W
Well classification:	Wildcat
Rotary table:	36 m above sea level
Well spud:	10 July 2000
Well termination:	4 September 2000
Total measured depth:	2973 m RT
Water depth:	1152 m
Core:	No conventional core taken
Sidewall core:	150 shots, 120 recoveries, 5 misfired and 25 lost
Logs:	Wireline: gamma ray, resistivity, density, neutron, sonic, caliper and SP MWD while reaming from 1920 m–TD: gamma ray, sonic, density, neutron, resistivity and acoustic caliper
Formation drilled:	Quaternary, Palaeogene and Campanian mudstone; Santonian sandstone
Hydrocarbons:	No hydrocarbons
Test:	MDT: 11 pressure points were tested and 1 fluid sample collected
Status:	Plugged and abandoned
Prospect type:	Upper Cretaceous reservoir with cross-cutting reflection in a major rotated fault block structure

Drilling of the Qulleq-1 well and release of data

The Qulleq-1 well was drilled by the Statoil group as part of their commitments in the eastern sub-area of the Fylla licence. The official well designation according to the existing block system is 6354/4-1, but the name Qulleq-1, which is derived from the Greenlandic word

Geology of Greenland Survey Bulletin 189, 24–33 (2001)

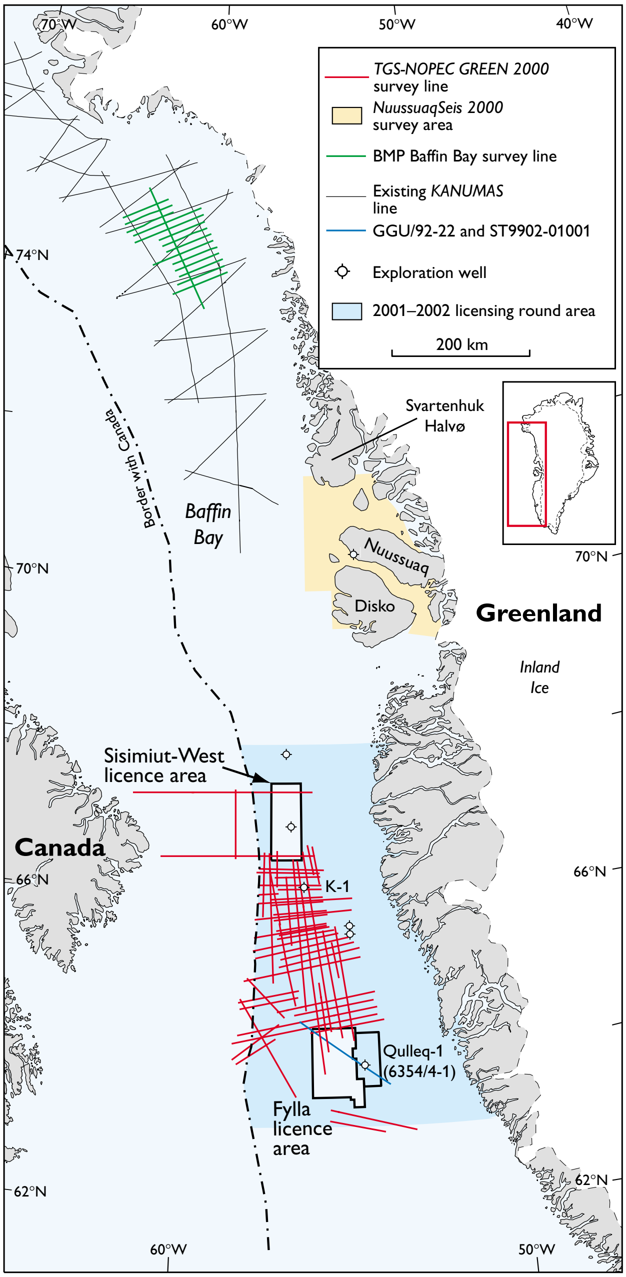


Fig. 1. Map of West and North-West Greenland showing seismic lines acquired during summer of 2000, licence areas and area covered by 2001–2002 licensing round. **K-1**: Kangâmiut-1 well.

Fig. 2. *West Navion* drilling off West Greenland in 2000. Photo courtesy of Smedvig asa.

for a train-oil lamp, has also been used by both Statoil and the authorities. The well was drilled with the newly built drill ship *West Navion* (Fig. 2). It was spudded in 1152 m water depth on 10 July and reached total depth (TD) at 2973 m below rotary table (RT) before it was plugged and abandoned in early September (see well data in Table 1).

Although the density of icebergs in the drilling region was higher than expected, downtime due to icebergs in the vicinity of the drill ship was only 33 hours (Ghexis 2000). On the other hand, there was approximately 4 weeks of downtime during the drilling period due to technical problems with the blow out preventer (BOP) and wellhead.

The sampling programme during drilling has given some limitations in interpretation of the results of the well, as no cores were taken. Furthermore, cuttings are not available from the uppermost ~ 600 m of the hole, because it was drilled riserless; only minor amounts of material were collected from this interval from the seabed using a remote operated vehicle (ROV). However, an extensive sidewall-core programme has been very important for biostratigraphic studies and also for interpretation of lithology. A total of 120 of 150 sidewall cores were recovered. Due to serious hole problems in the deeper part of the well, logging of the interval below ~ 2205 m could only be carried out during a wiper trip using 'Measuring While Drilling' (MWD) tools.

Some of the main results from the well are reported briefly below. Biostratigraphical, organic geochemical and petrographical details may be found in consultancy reports produced for the Statoil group (Bojesen-Koefoed *et al.* 2000; Nøhr-Hansen *et al.* 2000; Preuss & Dalhoff 2001; Preuss *et al.* 2001). All depths in the text and figures are in metres below rotary table (RT).

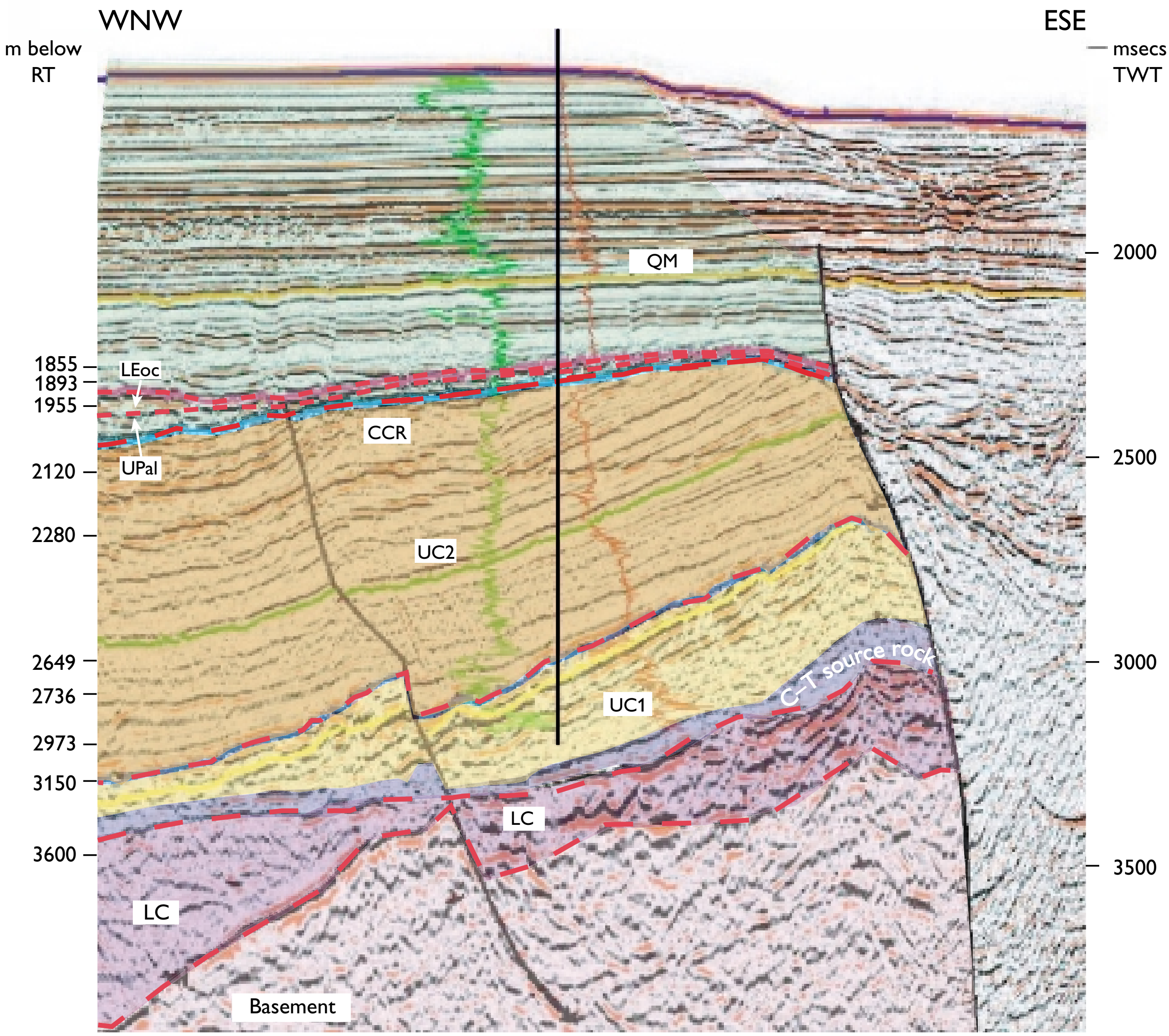


Fig. 3. Seismic line ST9902-01001 through the Qulleq-1 (6354/4-1) well. See Fig. 1 for position. The gamma-ray log is shown in **green** to the left of the well and the acoustic impedance log is shown in **red** to the right. Note that there is no significant change in acoustic impedance at the cross-cutting reflection (**CCR**) at 2537 msec TWT. **LC**: ?Lower Cretaceous; **UC**: Upper Cretaceous; **UPal**: Upper Paleocene; **LEoc**: Lower Eocene; **QM**: Quaternary – Middle Miocene. **TWT**: Seismic two-way-time.

Exploration targets

The main target of the Qulleq-1 well was the prominent cross-cutting reflection (CCR) which can be seen on the seismic data at around 2550 msecs two-way travel time (TWT) corresponding to a depth of *c.* 2100 m (Fig. 3). Extensive analysis of all data available prior to drilling (including amplitude versus offset (AVO) analysis of the seismic data) suggested that this reflection represented a gas–liquid contact in a compartmentalised turbidite sandstone succession (e.g. Bate *et al.* 1995; Aram 1999; Isaacson & Neff 1999). The well, however, encountered only mudstones in this interval and no gas or oil. At present, the nature of the CCR is not fully understood, but X-ray diffraction analysis of sidewall cores by Statoil suggests that it may be related to a phase-change transition from opal-CT mineralisation to quartz mineralisation.

Prior to drilling, TD was planned to 2850 m, just below a strong, regionally developed seismic reflection (~ 3100 msecs, Fig. 3), which was interpreted to be a source rock interval of possible Cenomanian– Turonian age. This reflection turned out to be the contact between Lower Campanian mudstones above and Upper

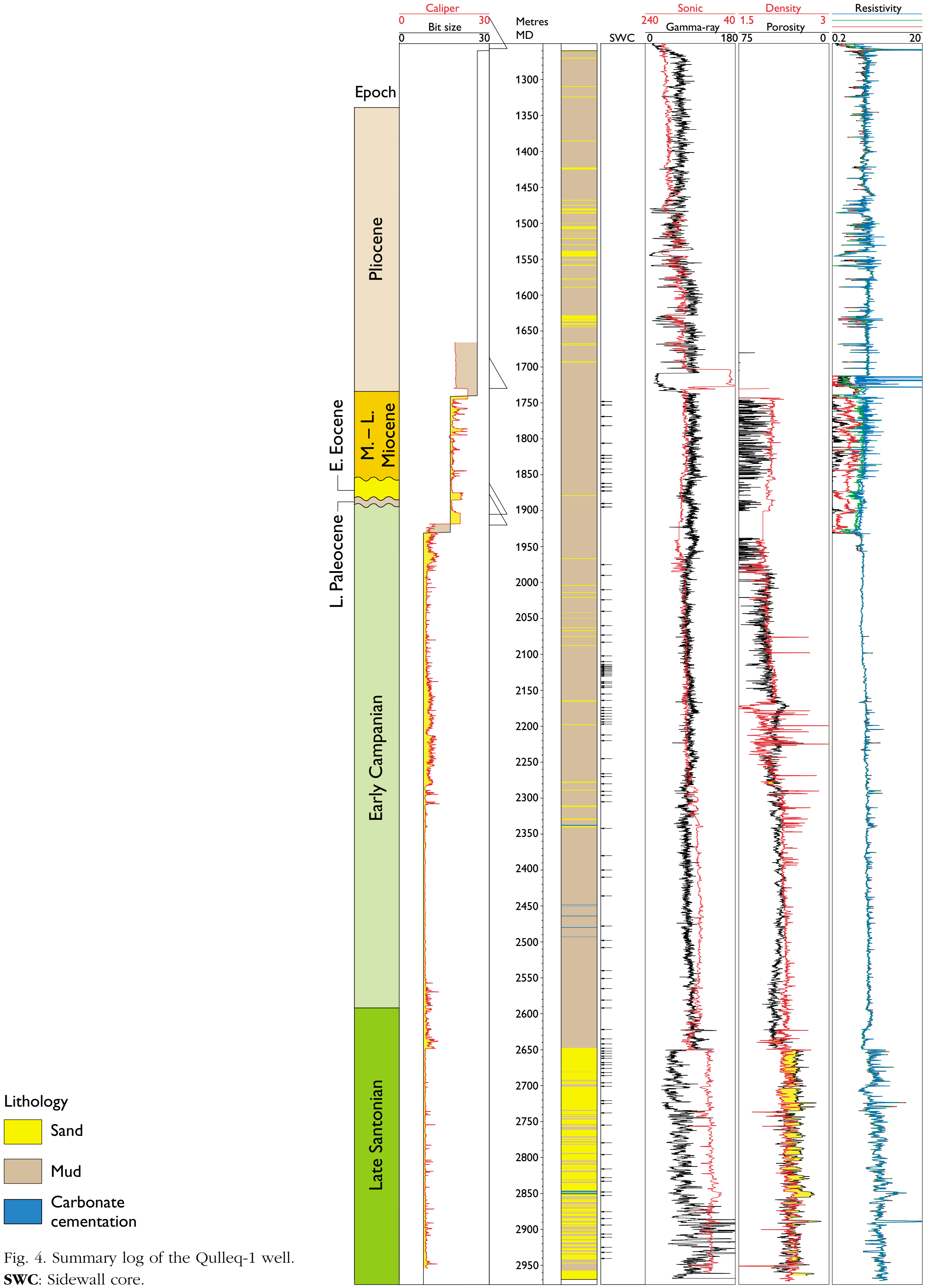


Fig. 4. Summary log of the Qulleq-1 well.
SWC: Sidewall core.

Santonian sandstones of reservoir quality below. As a result of the unexpected age and lithology of the sediments in this part of the section, and the lack of hydrocarbons at the CCR, it was decided to deepen the well to a maximum of 3000 metres. However, due to technical problems it was not operationally feasible to go deeper than the final TD of 2973 m.

The possibility of reaching deeper targets in the inferred Lower Cretaceous succession, or to penetrate the full stratigraphic succession to basement, was not considered by the Statoil group (Pegrum *et al.* 2001). At the actual drilling position, however, continued drilling, if undertaken, would penetrate deeper reservoir targets below structural closure and probably below spillpoint.

Stratigraphic units

With the new results from the Qulleq-1 well, it is now possible to interpret the seismic data from the region in more detail. Four major stratigraphic units including basement, a syn-rift succession seen in half-graben structures, a tilted fault-block succession and a draping, more or less flat-lying succession can be identified on the seismic data. However, only the upper two of these were penetrated by the well (Figs 3, 4).

The drilling demonstrated that the youngest unit draping the large, tilted fault-blocks of the Fylla structural complex consists of mid-Upper Paleocene to Quaternary mudstone-dominated, fully marine deposits (1152–1893 m). From outcrop and older well data, as well as from regional seismic data, two hiatuses spanning the interval across the Paleocene–Eocene boundary and the uppermost Middle Miocene to uppermost Early Eocene were expected, and their presence was confirmed at ~ 1885 m and ~ 1860 m, respectively. Prior to drilling, Statoil's well programme had identified several potential drilling risks in this unit including the presence of large boulders (dropstones) in the Pliocene–Quaternary succession, shallow gas in a possible sandstone interval (seen as a high amplitude reflection at ~ 1900 msecs on the seismic data), and possibly thin volcanic ash layers. Due to expected relatively low temperatures and the large water depth, the possibility of gas hydrates was considered a major risk while drilling and during any well control events. In the event, none of these risk elements were encountered during drilling. There was no evidence of shallow gas or gas hydrates, boulders were avoided and the age interval with possible volcanic rocks is missing due to a major hiatus.

Within the tilted fault-block succession two units differing in lithological and seismic character can be identified (Figs 3, 4).

The upper unit (1893–2649 m; 2318–3007 msecs) is characterised by good seismic reflectivity and lateral continuity although it is somewhat transparent (UC2 on Fig. 3). When drilled it was found to consist of fully marine mudstones of Early Campanian age (Fig. 4). The unconformity between the Palaeogene and the Upper Cretaceous penetrated by the well spans the Early Campanian to mid-Late Paleocene, representing about 12–15 million years (Nøhr-Hansen *et al.* 2000).

The lower unit (2650–2973 m; 3007 to ~ 3300 msecs) is characterised by good reflectivity and lateral continuity of units (UC1 on Fig. 3). The upper part of this unit comprises a fully marine, sandstone-dominated succession of Late Santonian age. The first possible Upper Santonian strata are found at 2635 m and, although the seismic data suggest an unconformity between the sandstone-dominated unit and the overlying mudstones, there is no evidence of a hiatus or condensed section (Fig. 4; Nøhr-Hansen *et al.* 2000).

The syn-rift succession (~ 3300 to ~ 3600 msecs) was not reached by the well but may be seen on the seismic data as a distinct change in seismic character (Fig. 3). The boundary with the overlying unit is unconformable and could represent a regionally mappable contact between Lower Cretaceous syn-rift sediments (fluvial or shallow marine) below and fully marine mid-Cretaceous/Upper Cretaceous sediments including a possible ?Cenomanian–Turonian source rock interval above.

Basement is difficult to delineate on the seismic data, but may be seen at around 3500 msecs at the well position in Fig. 3. The crystalline basement may, however, be covered by both Ordovician limestones and Jurassic sediments, since Jurassic spores have been found in sidewall cores in the well (Nøhr-Hansen *et al.* 2000).

Santonian reservoir sandstone

Qulleq-1 encountered ~ 90 metres of reservoir-quality sand below which is a sandstone-dominated unit down to TD also showing reservoir potential (Fig. 4). The gamma-log signature suggests that the penetrated Upper Santonian sandstone succession could be divided into three sub-units (Fig. 5). The sandstones are, however, both immature (with abundant feldspar, mica, pyroxene and rock fragments) and glauconitic. It is therefore not possible to relate the gamma-ray curve directly to sandstone/shale ratio. The main (upper) reservoir sandstone appears to exist within much or all of the struc-

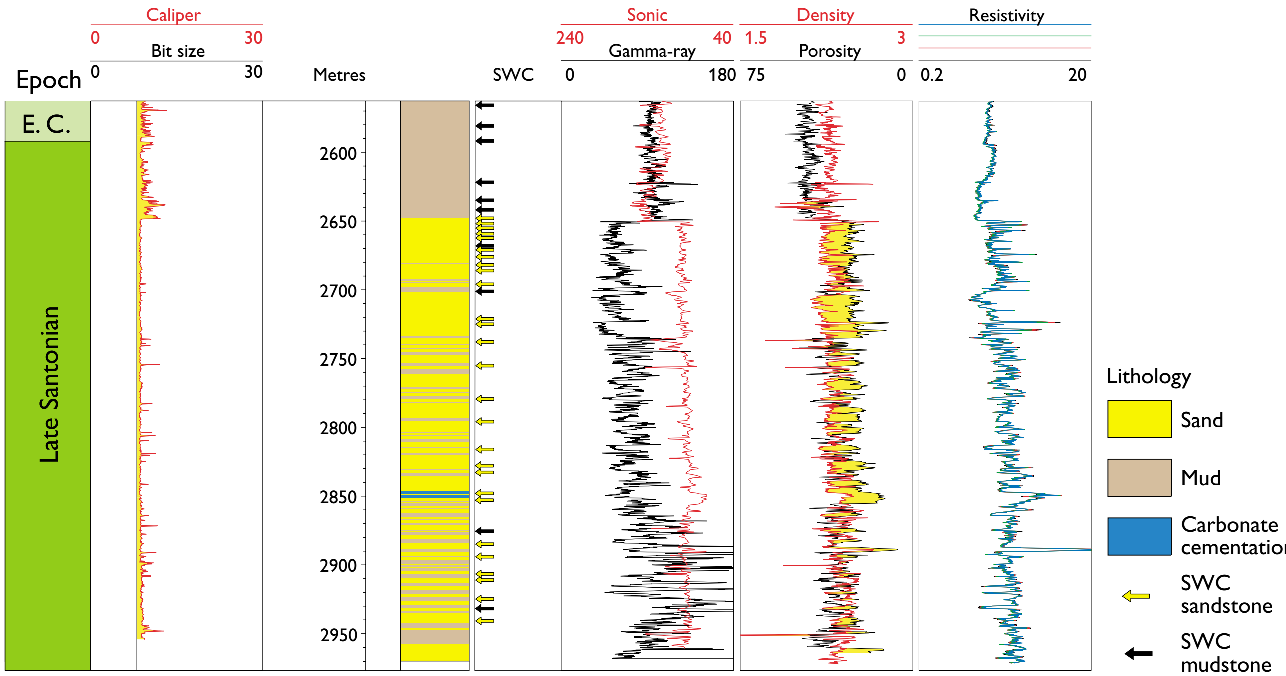


Fig. 5. Detailed log of the Santonian sandstone reservoir unit in the Qulleq-1 well. **SWC**: Sidewall core. **E.C**. Early Campanian.

ture shown in Fig. 8, but the character of the reflections changes from place to place indicating some changes in lithology or petrophysical properties. Unfortunately, the thickness of the best reservoir interval is close to seismic resolution, so it is not a simple task to relate the changes in seismic character to changes in lithology and reservoir properties.

Organic geochemistry and thermal maturity

Organic geochemical analyses of samples from the Qulleq-1 well were hampered by pervasive contamination by polyalkyleneglycol (PAG) – a drilling mud additive which was used in very high concentrations because of the risk of gas hydrates. Attempts to remove the contaminant failed, and Rock-Eval/TOC screening data from the well are therefore largely useless (see details in Bojesen-Koefoed *et al.* 2000). Generally, total organic carbon (TOC) values are below 0.5 wt% in the Palaeogene–Neogene mudstone unit, whereas most of the Lower Campanian marine mudstones show values between 1 and 2 wt%. The data show that no prolific petroleum source rocks are present within the drilled succession. Over the interval 2739–2811 m, a number of mudstone samples show relatively high TOC values (3–7 wt%). Mathematical curve-fitting carried out on original Rock-Eval pyrograms allowed elimination of the effects of PAG contamination, and showed that, despite high organic matter contents, these deposits possess only marginal source rock potential with corrected hydrogen indices (HI) < 120. Visual kerogen analyses confirm these results, showing the kerogen to consist predominantly of coaly and non-fluorescent amorphous organic matter.

Analysis of sandstones from sidewall cores was carried out in an attempt to detect traces of migrated petroleum, but the results showed only PAG and various other contaminants. No traces of migrated hydrocarbons were detected.

Since optical analyses were unaffected by PAG-contamination, a well-constrained maturity trend could be established (Fig. 6). Vitrinite reflectance (R_0) measurements show the succession to be immature with respect to petroleum generation. The top of the 'oil window' is projected to be at about 3160 m, corresponding to *c.* 200 m below TD of the well. No significant changes of vitrinite reflectance are observed across biostratigraphic hiatuses. Based on the projected vitrinite reflectance level at the seabed, it may be concluded that the succession is near its maximum depth of burial.

Basin modelling

With new knowledge on the thermal maturity and temperature gradients in Qulleq-1, together with a reinterpretation of the seismic data based on new lithological and biostratigraphic information, the 2D basin modelling of the Fylla area has been revised.

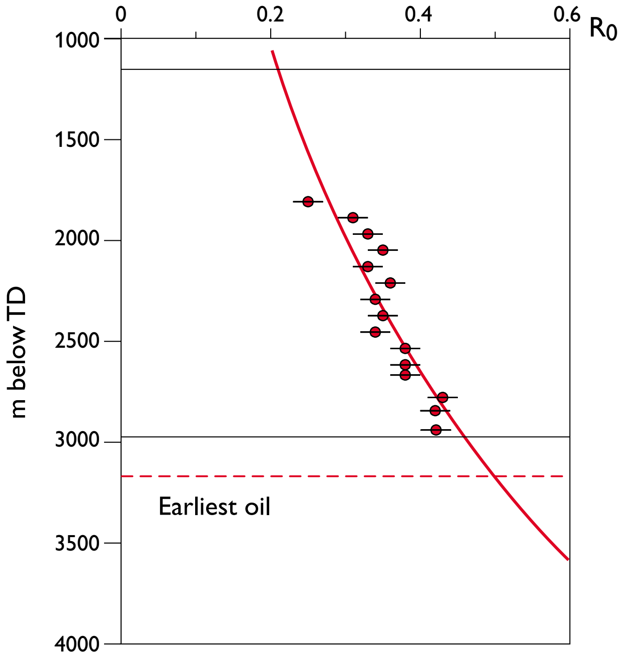


Fig. 6. Vitrinite reflectance versus depth in Qulleq-1.

The model clearly demonstrates that the sedimentary succession penetrated by Qulleq-1, as well as most of the succession underlying TD, is immature and that the assumed Cenomanian–Turonian source rock is immature in the vicinity of Qulleq-1 (Fig. 7). It is, however, evident from the modelling that this interval is situated in the main oil window in the two fault-blocks immediately east of Qulleq-1 (Fig. 7). The Cenomanian–Turonian is also inferred to be mature in the westernmost part of the Fylla licence area, although the lack of a seismic tie across the main fault zone makes it difficult to predict the position in detail. This suggests that the seismic line GGU/92-22 intersects three major kitchens for hydrocarbon generation, results which have very important implications for prospectivity. If the modelling data from line GGU/92-22 are used to predict the position of the oil generation zones throughout the Fylla area, and if there is a source rock in these localities, a number of other kitchens and migration pathways can be mapped (Fig. 8).

Seismic reinterpretation of the cross-cutting reflection

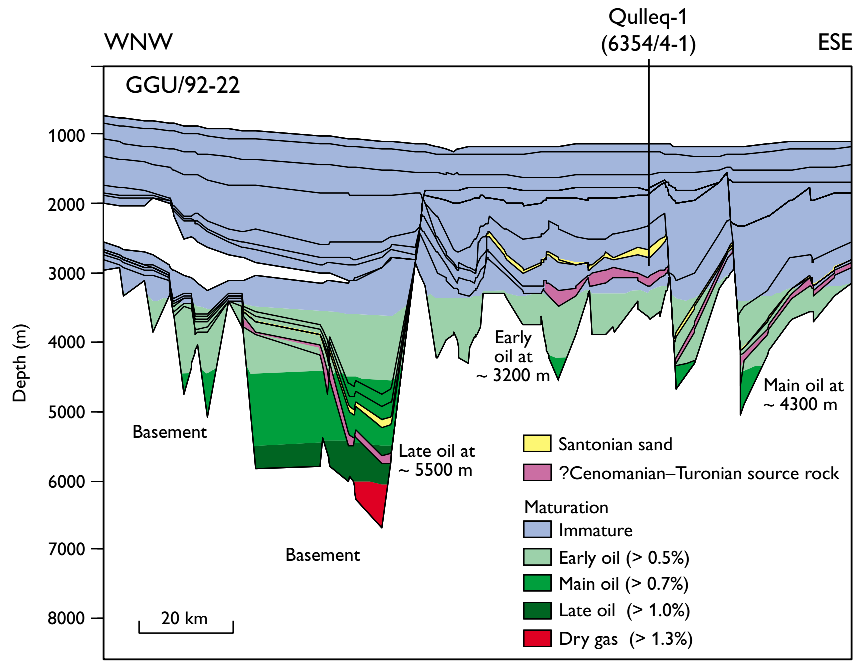
The results of the Qulleq-1 well show that the forecast Upper Cretaceous reservoir consists entirely of mudstone, and that the cross-cutting reflection (CCR) may be related to the phase transition from opal-CT to quartz. The acoustic impedance log shows no significant change in acoustic impedance at the depth of the CCR (Fig. 3), which raises the question about the origin of the prominent reflection. Isaacson & Neff (1999, fig. 13) show an increase of amplitude with offset for the CCR, and a decrease in amplitude with offset for the top Cretaceous reflection. These observations could indicate that there is significant seismic anisotropy within the opal-CT section. Such anisotropy could result in significantly different *horizontal* acoustic impedances in the opal-CT and quartz sections and little or no reflection of near vertical seismic energy, but significant reflection of far-offset rays. A stacked section which shows the summed contribution of both near- and far-offset energy, consequently shows the CCR from the far-offset traces only.

Summary of results

The drilling of the Qulleq-1 well, not unexpectedly, gave some surprises. Organic geochemistry, biostratigraphy, log interpretation and seismic reinterpretation have provided new information of importance for assessment of the petroleum potential of offshore West Greenland.

1. Seismic velocities in the Qulleq-1 well are distinctly lower than in all other wells in West Greenland.
2. In contrast to all the previous wells (Rolle 1985) there is surprisingly little sand in the Neogene succession.
3. Several of the drilling risks considered before drilling are now known not to apply to this part of the basin.
4. The major hiatuses in and bounding the Palaeogene were expected and their ages confirmed.
5. The age and lithology of the seismic units within the tilted fault-blocks were not as expected. The upper units are somewhat older than expected, and consist of mudstone where substantial amounts of sand were expected (Bate *et al.* 1995; Aram 1999; Isaacson & Neff 1999). The deeper units are significantly younger (Santonian instead of Aptian/Albian) and reservoir-quality sand was found where it was hoped to encounter Cenomanian–Turonian source rock. This information has both negative and positive implications for the exploration possibilities.
6. The CCR is not related to a gas–liquid contact. The ‘flat spot play’ in the Fylla licence area seems to be dead.
7. The well-penetrated sediments are only immature for oil generation, and the main oil window (peak generation) is deeper than TD.

Fig. 7. 2D basin modelling of seismic line GGU/92-22 using the IES PetroMod® 2D modelling software. The model describes all important basin processes and data as a function of time. The figure shows the subdivision used in Qulleq-1 with modelled thermal maturity on a modelled depth-converted seismic line. Note the position of the Santonian sand unit and the possible Cenomanian–Turonian source rock interval in the kitchens east and west of Qulleq-1. See Fig. 1 for position of seismic line.



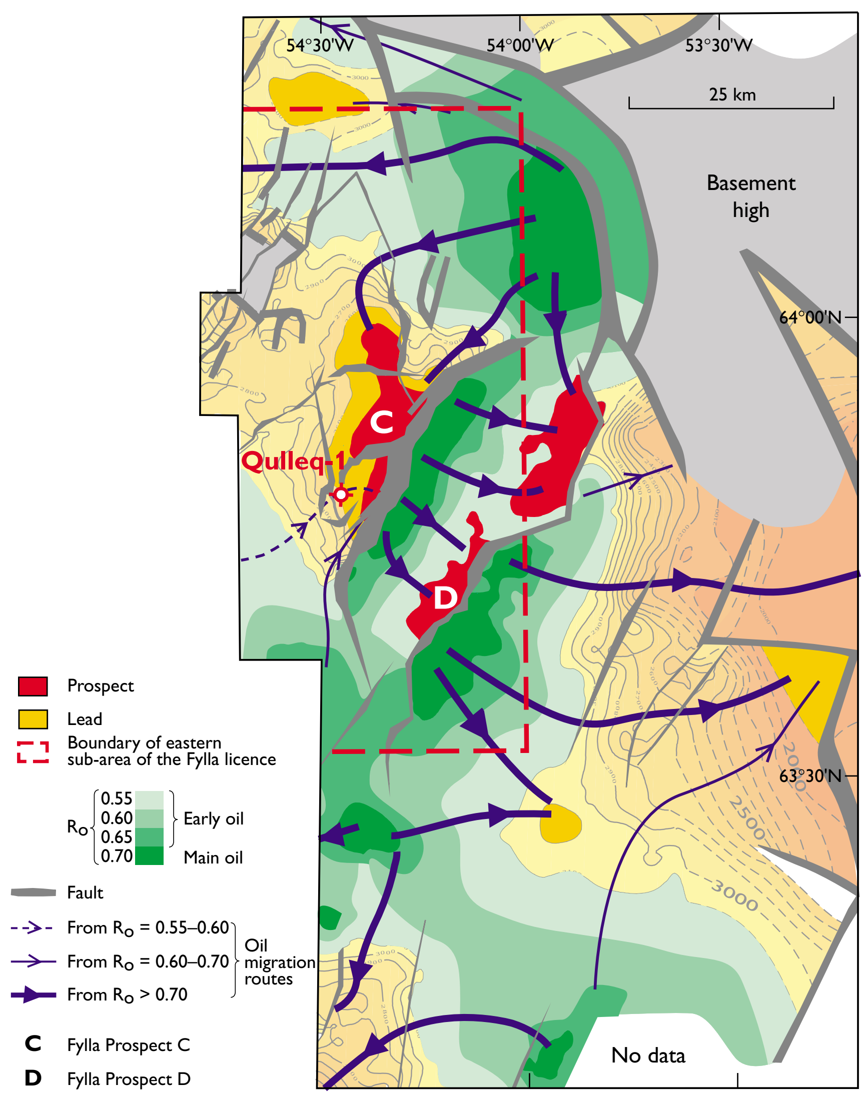


Fig. 8. Map showing depths in metres below sea level to the top of the Santonian sandy interval penetrated by Qulleq-1 at 2749 metres below rotary table. The crest of the structure is more than 800 metres shallower than the depth at which the well penetrated the horizon. Overlain colours indicate where a potential Cenomanian–Turonian source rock may be mature. Migration routes of oil from kitchen areas to leads and prospects are indicated. **Grey areas** represent faults.

8. Thermal maturity data show a simple trend and are in accordance with measured temperatures. This is not a surprise and makes exploration simpler.
9. The Qulleq-1 well was not drilled deeply enough, neither stratigraphically nor in absolute depth, considering the frontier nature of the Fylla area. Prospective successions of both presumed Early and Late Cretaceous age were left untouched below TD.
10. The Santonian reservoir sandstone that was found was penetrated more than 800 m below the crest of the prospect, and significant up-dip potential on the structure remains untested.

Implications for prospectivity

The results from the Qulleq-1 well have significant implications for the evaluation of the prospectivity of the region. For many years the main risk in assessing the potential of offshore West Greenland has been the question of whether or not oil-prone source rocks are present (see first discussion in Chalmers *et al.* 1993). This risk was considerably reduced with the finds of widespread oil seeps onshore in the Disko–Nuussuaq region (see Christiansen *et al.* 1994; Bojesen-Koefoed *et al.* 1999). Although the results of Qulleq-1 were not as hoped, they have neither increased nor decreased this risk, since the well did not reach the postulated Cenomanian–Turonian succession which is considered to be the most likely oil-prone source rock interval in the region.

The nature of the CCR is unrelated to hydrocarbon charge. The lack of high gas readings during drilling, and the lack of petroleum traces in cuttings and sidewall cores may be arguments for a higher risk of especially the presence of a source rock for gas. However, the well drilled mainly through immature mudstones, and the only potential reservoir sandstones were penetrated 700–800 m below the crest and close to spillpoint of the structure.

The thermal maturity data and basin modelling suggest that a possible Cenomanian–Turonian oil-prone source rock would be mature in kitchens in the deeper synclines of the Fylla area fault-blocks, and that there are simple migration pathways into several large prospects with four-way dip closure; however, the well was on none of them (Fig. 8). One significant reservoir interval in the Upper Santonian has been demonstrated, and other reservoir sandstones may be present below the unconformity that is seen on the seismic data some hundred metres below TD of the Qulleq-1 well. The thick Campanian and Palaeogene–Neogene mudstone successions form an excellent seal to these prospects.

Seismic acquisition during summer 2000 – the Canadian connection

In the summer of 2000 three seismic vessels operated in the waters off West and North-West Greenland. The seismic company TGS-NOPEC extended their 1999 acquisition of non-exclusive seismic data in the area designated for the licensing round in 2001 (Fig. 1). The seismic survey vessel *Zephyr* acquired more than 6300 km of seismic data, mainly in the region between the Sisimiut-West and Fylla licence areas. In particular, the data coverage around the Kangâmiut-1 well (the Kangâmiut Ridge area) was improved considerably (Fig. 1). In order to link the Canadian and Greenland basins, TGS-NOPEC acquired three tie lines in Canadian waters. The TGS-NOPEC seismic data base off West Greenland now comprises more than 9000 km of high-quality data.

The Danish fishery inspection vessel *Thetis*, with seismic equipment and operated by Nunaoil, acquired proprietary seismic data within the Sisimiut-West licence area for the Phillips group (about 1200 km). The Bureau of Minerals and Petroleum (BMP), Nuuk, Greenland, funded a seismic survey in the Baffin Bay area of North-West Greenland. The survey was designed as infill to the existing regional KANUMAS survey in order to achieve a denser seismic coverage of leads observed on the KANUMAS lines. A total of 1340 km were acquired (Fig. 1).

GEUS used the Danish research vessel *Dana* to acquire high-resolution seismic data in the waters around Nuussuaq. This programme (*NuussuaqSeis 2000*) was undertaken in co-operation with Aarhus University, Denmark, and was funded by the Danish Energy Research Programme and BMP. This project aims to improve understanding of the structure of the shallow part of the Nuussuaq Basin. The new data will also have direct implications for assessing the hydrocarbon potential of the onshore areas. Due to excellent weather and favourable ice conditions, more than 2700 km of data were acquired in only 18 days (see Marcussen *et al.* 2001, this volume).

Onshore field work and other activities

For the first time in more than 10 years there was no petroleum-related onshore field work in the Disko–Nuussuaq–Svartenhuk Halvø region in 2000. Activities were restricted to a field trip organised by TGS-NOPEC with GEUS providing guidance in the field.

The extensive field programme that GEUS and collaborating partners have carried out throughout the

1990s has reached a temporary conclusion. Many of the results from this work are important for the evaluation of the exploration potential of the Nuussuaq Basin itself and also for the offshore areas. Several important studies have been published in 2000, including the structures of Svartenhuk Halvø (Larsen & Pulvertaft 2000), evidence of an Early Campanian rift-phase on Nuussuaq (Dam *et al.* 2000), specific compounds in seeping oils (Nytoft *et al.* 2000), a possible play showing seismic anomalies west of Disko (Skaarup *et al.* 2000) and documentation of major Neogene uplift in West Greenland (Chalmers 2000). Many other studies on basin history, sedimentological and structural models, lithostratigraphy, organic geochemistry of northern seeps etc. are in progress.

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Acquisition of high-resolution multichannel seismic data in the offshore part of the Nuussuaq Basin, central West Greenland

Christian Marcussen, James A. Chalmers, Holger Lykke Andersen, Rasmus Rasmussen and Trine Dahl-Jensen

A high-resolution multichannel seismic survey (project *NuussuaqSeis 2000*) was carried out from 18 July to 2 August 2000 in the offshore part of the Nuussuaq Basin, central West Greenland using the Danish research vessel R/V *Dana* with seismic equipment from the Geological Institute, Aarhus University, Denmark. Funding for the project was provided by the Danish Energy Research Programme, the Bureau of Minerals and Petroleum, Nuuk, Greenland, the Geological Institute of Aarhus University and the Geological Survey of Denmark and Greenland (GEUS). After completion of the *NuussuaqSeis 2000* project, R/V *Dana* was used for a three-day coring project in Disko Bugt (see Kuijpers *et al.* 2001, this volume) before the ship returned to Denmark.

Background

Knowledge of the Nuussuaq Basin in central West Greenland (Fig. 1) has increased significantly since the discovery of extensive oil seeps on western Nuussuaq in 1992 (Bojesen-Koefoed *et al.* 1999). A number of geological and geophysical studies have been published and data from slim core drilling and exploration wells are also available. The existence of the oil seeps indicates that the Nuussuaq Basin is a petroleum basin in its own right, and not merely an accessible analogue to potential petroleum basins offshore (Bojesen-Koefoed *et al.* 1999). Seismic data acquired onshore in 1994 (Christiansen *et al.* 1995), followed by a seismic and gravity survey in 1995 in the fjords south and north of Nuussuaq, have greatly improved the general understanding of the structure of the basin (Chalmers *et al.* 1999a). Project *NuussuaqSeis 2000* – acquisition of high-resolution multichannel seismic data in the waters around Nuussuaq and Ubekendt Ejland – was designed to improve understanding of the shallow structure of the Nuussuaq Basin.

The seismic survey

Planning

Experience during seismic acquisition in earlier years in the same waters has shown that use of a long streamer (e.g. 3000 m) is likely to be prevented by the large numbers of icebergs. While usage of a short streamer makes it impossible to remove seabed multiples by traditional methods (e.g. F/K filtering), the relatively large water depths in the area of interest – between 400 and 800 m – make it possible to see up to 1.5 km of sediments before the first seabed multiple obscures the data. It was therefore decided to accept the limitations of a short streamer, and use high-resolution seismic equipment with a considerably smaller source but better resolution than conventional marine seismic equipment.

Prior to initiation of the survey, all available bathymetric data were compiled and plotted together with the planned lines as overlays to the published charts from the area. This showed that the bathymetry of parts of the survey area was poorly known. The planned survey consisted of 2013 km of priority 1 lines in Vaigat and Uummannaq Fjord plus 290 km of priority 2 lines over the areas underlain by basalt west of Nuussuaq and Ubekendt Ejland.

Seismic equipment

The seismic acquisition system used for the survey is owned by the Geological Institute of Aarhus University. It includes a 96-group, 594 m long hydrophone streamer with a 6.25 m group interval and two Geometrics R48 recording systems. The source consisted of a 4×40 in^3 sleeve-gun cluster. Navigation was controlled by Navipac software, and positioning was provided by an Ashtech G12 GPS receiver (see Table 1 for details). A Ramesses quality-control system is integrated in the acquisition system to provide real-time processing and display

Geology of Greenland Survey Bulletin 189, 34–40 (2001)

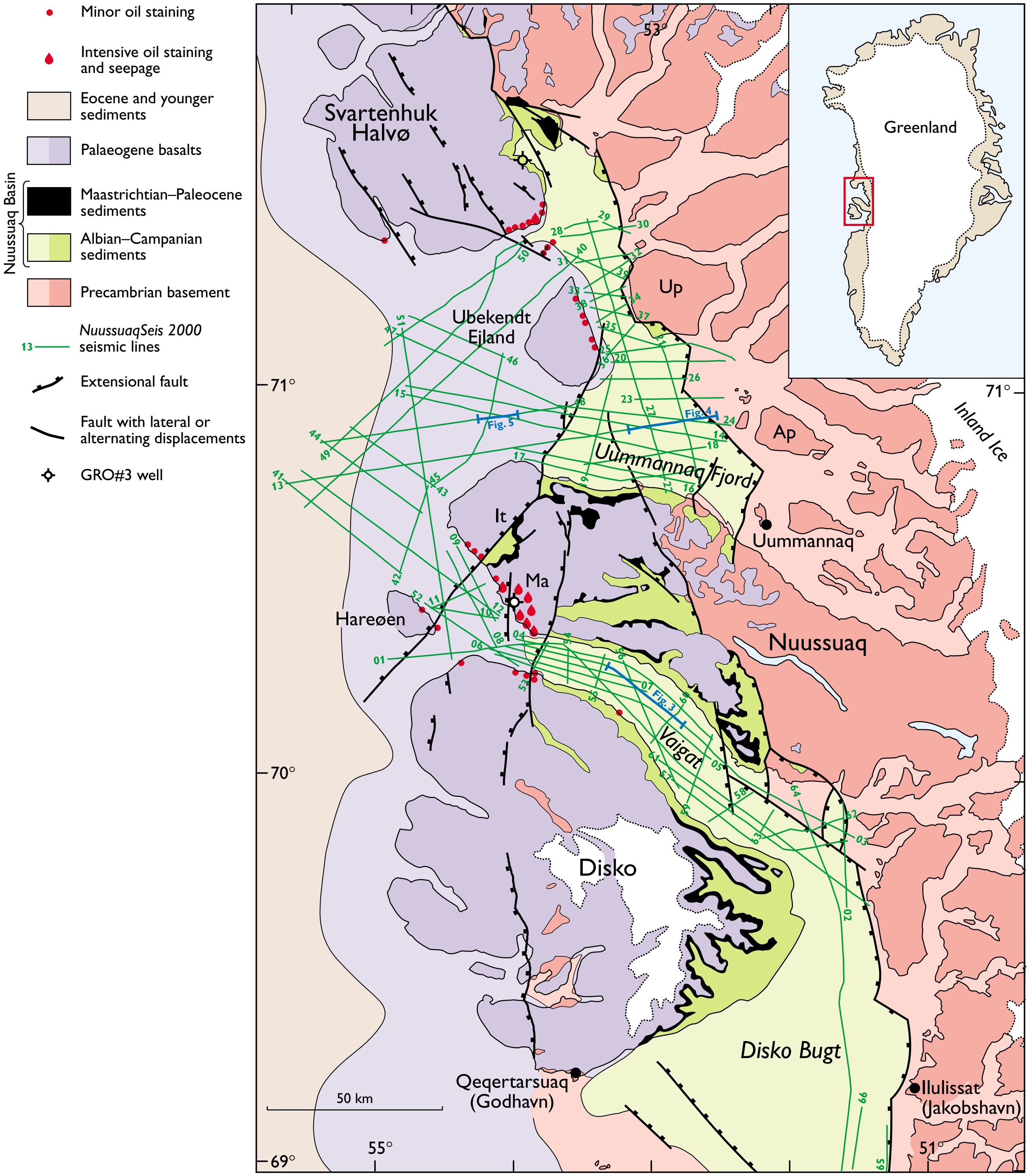

Fig. 1. Simplified map of the Nuussuaq Basin showing the geology onshore (dark colour tones) and offshore (light colour tones), place names used in text and the seismic lines acquired during project *NuussuaqSeis 2000*. The prefix GEUS00- is omitted from all line numbers. Location of the seismic examples in Figs 3, 4 and 5 are shown. **Ap**: Appat Ø, **It**: Itilli fault, **Ma**: Maarrat, **Up**: Upernivik Ø. White areas are ice. Modified from Christiansen *et al.* (2000).

Table 1. Acquisition equipment and parameters

	Equipment / Parameters
Source	4 x 40 in^3 TI SG-I sleeve guns
Spacing between individual guns	50 cm centre to centre
Depth	3.5 m to centre of cluster
Pressure	120 bar
Streamer	HydroScience
Length	593.75 m (active section)
Towing cable length	90 m
Number of groups	96
Group interval	6.25 m
Group length	3.125 m
Streamer depth	3 m
Near offset	53 m
Shotpoint interval	5 sec ≈ 12.5 m
Recording system	2 Geometrics R48 Sample rate: 1 msec
Record length	3072 msec
Delay	0 msec
Filters	Low cut: 10 Hz slope 24 db/oct High cut: 300 Hz anti-aliasing
Data format	SEG-D 8048 revision 0
Output media	IBM 3490 cartridge
Navigation	GPS - Ashtech G12 receiver
Magnetometer	Geometrics G866
Echosounder	Simrad EK 400

facilities. Due to technical problems, magnetic data were recorded only from line GEUS00-18.

A ProMax processing system from GEUS was installed on R/V *Dana* (Fig. 2); this system was used for test processing of the seismic data and hence gave valuable input for subsequent adjustments of the survey programme.

Data acquisition

A total of 2743 km of data were acquired during the 18-day survey, which was 20% more than planned (Fig. 1; Marcussen *et al.* 2001). During the entire cruise, the weather was effectively calm and therefore ideal for seismic acquisition. Icebergs, which were expected to be the main obstacles to seismic acquisition, were either relatively sparse, in which case it was possible to acquire data around them without significant problems other than the occasional move slightly off-line, or they were packed so densely that some areas were impossible to penetrate. The amount of time lost for equipment downtime was also small, a total of about 10 hours. Maintenance of equipment was mostly undertaken during extended line shifts.

Data were acquired in three areas: (1) the Vaigat area south of Nuussuaq; (2) the area of Uummannaq Fjord and the strait between Ubekendt Ejland and Upernivik Ø; and (3) the areas west of Ubekendt Ejland and Nuussuaq where basalts are exposed on the seabed. A preliminary interpretation of the data was made onboard as it became available throughout the survey. The primary purposes of the interpretation were to provide information for any necessary alteration of survey plans, to judge the quality of data, to provide input to processing on ProMax, and to develop models for subsequent more detailed interpretation.

Vaigat

Chalmers *et al.* (1999a) divided the Vaigat area, the sound between Disko and Nuussuaq, into three distinct parts. West of about 54°W, basalt is exposed at the seabed (Fig. 1). Between longitudes 54°W and 53°W, three large fault-blocks with thick, easterly dipping, Cretaceous sediments can be seen. The centre of the bathymetric channel is partly filled by flat-lying Holocene

Fig. 2. The Danish research vessel R/V *Dana* in Uummannaq Fjord during project *NuussuaqSeis 2000.*

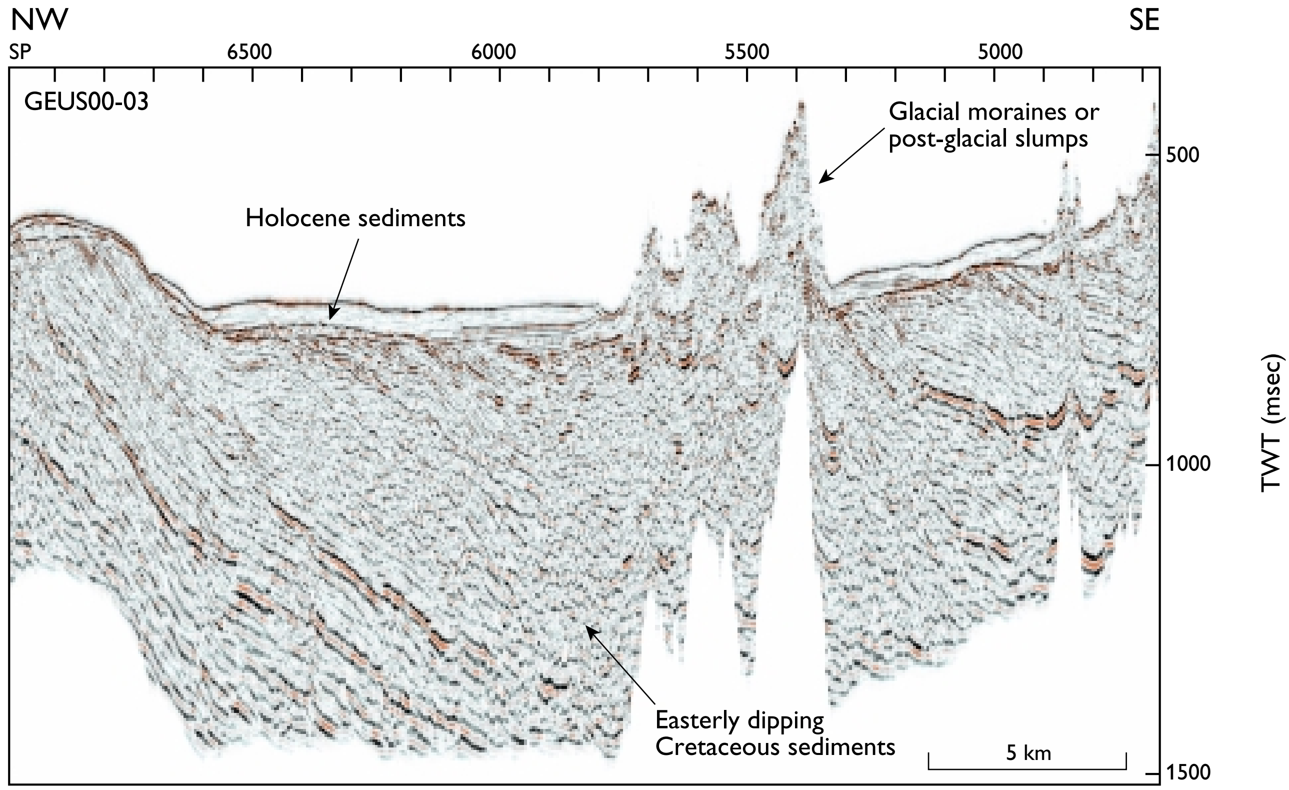

Fig. 3. Example of seismic data from Vaigat. Part of line GEUS00-03 showing easterly dipping Cretaceous sediments beneath flat-lying Holocene sediments with large glacial moraines or post-glacial slumps. Location shown in Fig. 1. **SP**: shot point.

sediments (Fig. 3). The area east of 53°W is complex, with both large glacial moraines or post-glacial slumps and sills at and beneath the seabed (Fig. 3).

The first phase of the survey in Vaigat was carried out for the most part on the pre-planned lines. Since the iceberg density was low, the strategically most important data was acquired first over the known area of fault-blocks in western Vaigat. It became apparent during the acquisition of these first lines that the quality of the data was good to excellent in those areas without sills, large glacial moraines or post-glacial slumps at the seabed (Fig. 3).

Preliminary interpretation of the lines acquired in western Vaigat showed that the interpretation shown in Chalmers *et al.* (1999a) was essentially correct, and in the second phase of the survey in this area a number of lines were planned to cross the western part of the fjord within each fault-block to provide horizon ties between the lines along the fjord.

Eastern Vaigat has a complex structure, and the interpretation shown in Chalmers *et al.* (1999a) requires revisions. Additional lines were acquired to optimise new interpretations of the structure.

A few lines were acquired in the area off Maarrat between Nuussuaq and Hareøen in order to test whether correlation of the onshore geology and the results of the GRO#3 exploration well to the offshore areas was possible.

Uummannaq Fjord and the strait between Ubekendt Ejland and Upernivik Ø

The area north of Nuussuaq is characterised by large fault-blocks with thick, easterly dipping, Cretaceous sediments (Chalmers *et al.* 1999a). The fault-blocks are divided by faults that throw down to the west and can be identified as offshore extensions of faults known onshore (Fig. 2). To the east Precambrian basement is exposed, whereas west of the offshore extension of the Itilli fault basalt is exposed at the seabed.

Acquisition started in this area with line GEUS00-13, a long transect from west of Nuussuaq to basement outcrop west of Appat Ø. On the way into and across Uummannaq Fjord, it became apparent that there was a low density of icebergs in the outer fjord similar to that encountered in Vaigat, but icebergs were tightly

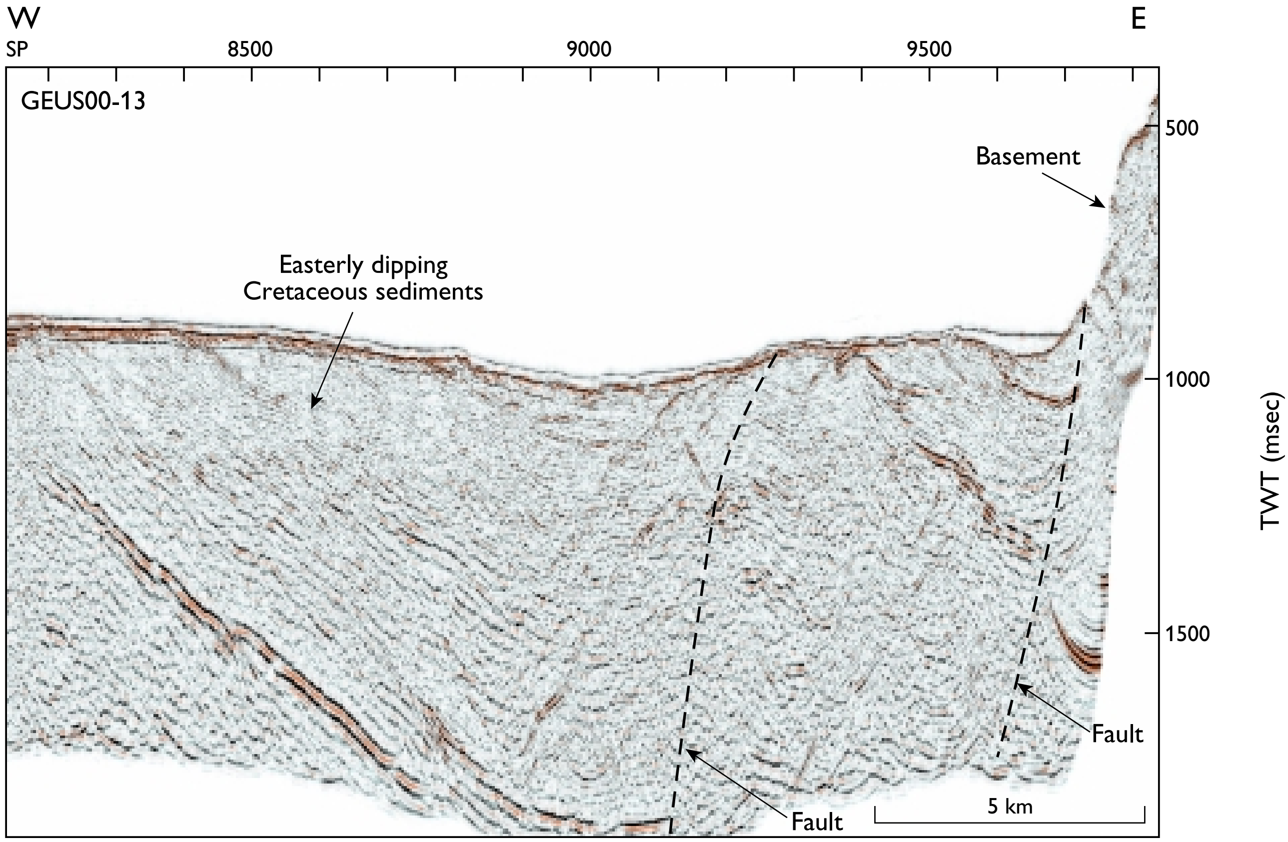

Fig. 4. Example of seismic data from Uummannaq Fjord. Part of line GEUS00-13 showing easterly dipping Cretaceous sediments in fault-blocks with Precambrian basement outcrop at the eastern end. Location shown in Fig. 1. **SP**: shot point.

packed in the inner part of the fjord around Uummannaq.

Of two long transits (GEUS00-14 and -15) across Uummannaq Fjord to the basalt area and back, the eastern end of line GEUS00-15 was terminated early because of dense concentrations of icebergs. Further acquisition of planned lines east of 52°30′W had to be abandoned because of densely packed icebergs, and thus only a few crossings over the eastern margin of the basin were made. New lines were planned in the accessible part of the fjord. After finishing work in the southern part of Uummannaq Fjord, a transit to the north between Ubekendt Ejland and Upernivik Ø (GEUS00-22 and -27) was terminated by large concentrations of icebergs at 71°27′N. It was not possible to proceed farther north, and the entire programme east of Svartenhuk Halvø in the northern part of the basin was abandoned.

Good reflections were obtained on most of the lines acquired and only few areas of moraine or large sills were noted. The area comprises fault-blocks, and good images of many of the faults were obtained (Fig. 4). Along the eastern margin of the area, several crossings from Cretaceous sediments to Precambrian basement were achieved (Fig. 4), and many images were also obtained of the margin of the basalts, as well as reflections from below the top of the basalts.

Areas west of Ubekendt Ejland and Nuussuaq where basalt is exposed at the seabed

Acquisition of lines west of Nuussuaq and Ubekendt Ejland was only a second priority. However, the favourable weather conditions made it possible to expand the acquisition programme considerably in this structurally poorly known area. Additional lines were thus acquired where basalts are found near the seabed, and water depths were large enough to achieve significant penetration of the basalts above the first seabed multiple.

Older seismic surveys in this area (GGU/1995 and Brandal/1971; Chalmers *et al.* 1999a) have shown that there are reflections from below the top basalt reflection. The significance of these reflections is, however,

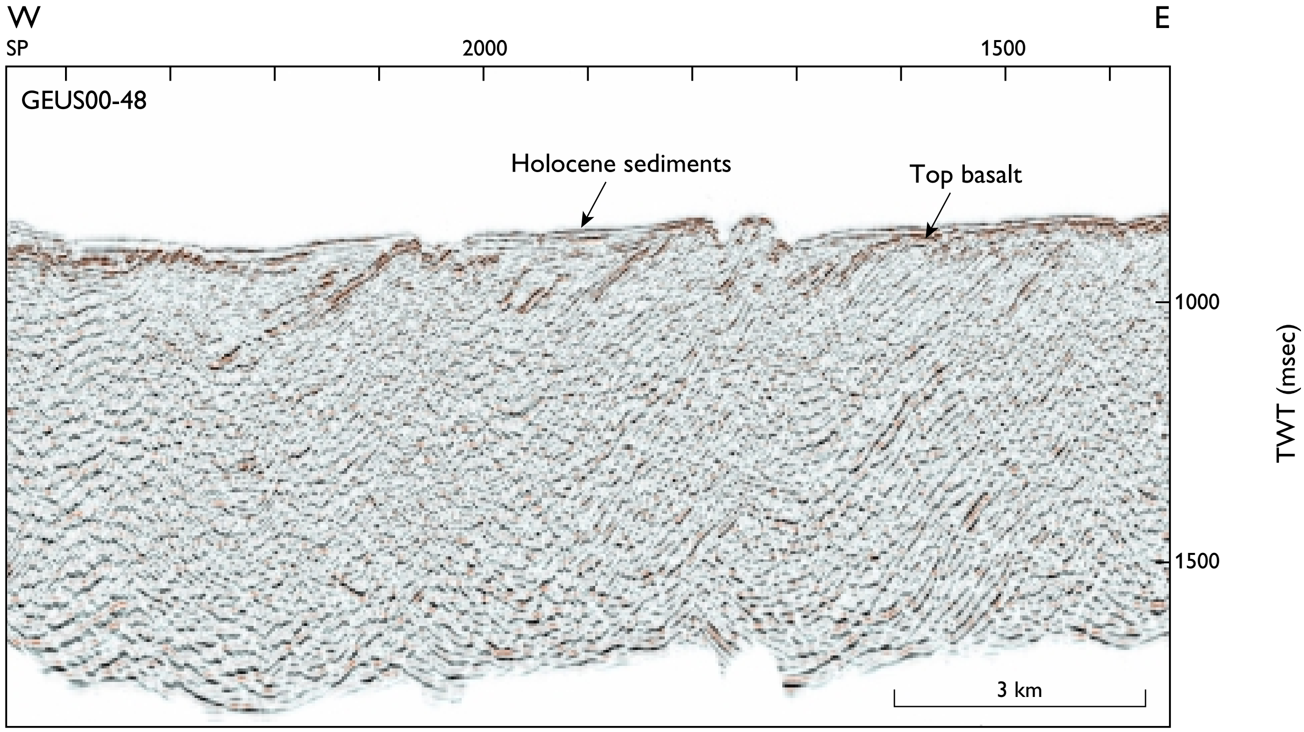

Fig. 5. Example of seismic data from the area north-west of Nuussuaq where basalts crop out at the seabed. Part of line GEUS00-48. The dipping reflections may come from syn-magmatic half-grabens or westward-dipping Cretaceous or lower Paleocene sediments (see text). Location shown in Fig. 1. **SP**: shot point.

not well understood; the different interpretations of the area so far published (Whittaker 1995, 1996; Geoffroy *et al.* 1998; Chalmers *et al.* 1999b) have substantially different implications with respect to its prospectivity. The presence of a type IV AVO (amplitude versus offset) anomaly associated with a bright spot on some of the GGU/1995 lines (Skaarup & Chalmers 1998; Skaarup *et al.* 2000) has significance from the point of view of hydrocarbon prospectivity.

Approximately 710 km of data were acquired in a broad grid extending from the mouth of Vaigat in the south to Svartenhuk Halvø in the north during a 3.5-day period. Excellent reflections were received from up to and over 500 msec below the top of the basalts in many areas (Fig. 5). Some of these sub-top basalt reflections are undoubtedly from lithological variations within the basalt sequences and preliminary correlation of the magnetic and seismic data suggests that it may be possible to develop a detailed seismic and magneto-stratigraphy. Other reflections seem to come from half-grabens (Fig. 5). While it is possible that the latter are syn-magmatic, as discussed by Geoffroy *et al.* (1998), it is also possible that they derive from westward-dipping Cretaceous or lower Paleocene sediments beneath thin basalts west of Nuussuaq. Quantitative interpretation of the magnetic data may resolve this question.

Processing

As noted above, the seismic data processing was initiated during the survey on selected lines, both to check data quality and to contribute to adjustments in the survey programme. The possibilities of removing the sea-bottom multiple were carefully tested, but although it was possible to weaken the sea-bottom multiple substantially, it was still too strong to identify primaries below the multiple except in a few places. This problem was expected because of the source strength (160 in^3 in total) and in particular the streamer length (600 m). In order to avoid problems in migration, it was therefore decided not to migrate the data below the sea-bottom multiple. The relatively time-consuming Kirchoff migration algorithm has been used to ensure a proper migration of the steeply dipping features common in the survey area. The velocity analyses show very high velocities in general, not only in areas covered by basalt, but also in the sediments below the Quaternary cover in most of the survey area, and in particular in Vaigat.

Summary

The cruise was very successful. Due to very favourable weather and ice conditions, 2743 km of good quality data were acquired, nearly 20% more than originally planned. High concentrations of icebergs prevented acquisition of data in the eastern part of Uummannaq Fjord and east of Svartenhuk Halvø.

Data from project *NuussuaqSeis 2000* have increased considerably the seismic coverage in the region, and it is anticipated that the new data will have direct implications for the evaluation of the hydrocarbon potential.

Acknowledgements

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Late Quaternary circulation changes and sedimentation in Disko Bugt and adjacent fjords, central West Greenland

Antoon Kuijpers, Jerry M. Lloyd, Jørn B. Jensen, Rudolf Endler, Matthias Moros, Laura A. Park, Bernd Schulz, Karin Gutfelt Jensen and Troels Laier

Several important outlets for meltwater and iceberg discharge occur along the margin of the Greenland Inland Ice. One of these is Disko Bugt in central West Greenland (Fig. 1). Large-scale exchange processes between the deep ocean and atmosphere are highly sensitive with regard to meltwater fluxes and global climate change. The Greenland Sea and Labrador Sea (see Fig. 1) with adjacent waters are the only regions in the Northern Hemisphere where deep-water formation occurs. New evidence shows that this process appears to be highly variable (e.g. Sy *et al.* 1997). Thus, meltwater production and iceberg calving from the Inland Ice margin of West Greenland may play a crucial role in controlling deep-water formation, notably in the Labrador Sea.

In order to examine the sensitivity of the Inland Ice margin to climate change, the UK Natural Environment Research Council (NERC) has since 1998 supported a project coordinated by Durham University. The project has included both land-based studies focusing on post-glacial sea-level rise and the regional ice sheet history since the last glaciation as well as offshore investigations. While the Institute of Geography, University of Copenhagen, is a project partner for the onshore investigations, the Geological Survey of Denmark and Greenland (GEUS) has contributed with marine geological work and expertise. In summer 1999 a 10-day cruise was carried out with the R/V *Porsild* from the Arctic Station in Qeqertarsuaq/Godhavn. During this cruise short sediment cores and surface sediment were collected, and hydrographic measurements were also made (Lloyd *et al.* 1999). With financial support from the Danish Natural Science Research Council, a further cruise was carried out by the R/V *Dana* from 3 to 6 August 2000. The objective was to collect longer piston cores for the study of late Quaternary palaeo-oceanographic changes in the Disko Bugt area, in particular with respect to meltwater and iceberg fluxes from the Inland Ice. In addition, relevant high-resolution shallow seismic information was to be obtained. On this occasion, a 12 m piston coring system newly acquired by GEUS was successfully operated from R/V *Dana* for the first time.

In this article the main results from the R/V *Dana* cruise are reported, as well as some of the previous findings from the 1999 cruise with R/V *Porsild*. In addition, some of the preliminary results from post-cruise laboratory work are referred to, amongst others that by the Baltic Sea Research Institute in Warnemünde, Germany.

Regional setting and previous work

Water depth in the western and eastern part of Disko Bugt is generally between 200 m and 400 m. This area has a generally very rugged sea floor, with frequent outcrops of Palaeogene rocks, hummocky glacial deposits, and widespread evidence of iceberg scouring (Brett & Zarudzki 1979). An up to 990 m deep valley (Egedesminde Dyb, see Fig. 1) extends across Disko Bugt from the area between Kronprinsen Ejland and Hunde Ejland to the shelf edge further to the south-west, where a fan system is found (Zarudzki 1980). Very little is known about the late Quaternary palaeo-oceanographic development of the area. During the last glaciation a major outlet glacier from the Inland Ice probably covered large parts of Disko Bugt (Ingólfsson *et al.* 1990; Bennike *et al.* 1994). Holocene sedimentary and hydrographic conditions in fjords at the west coast of Disko have recently been described by Gilbert *et al.* (1998) and Øhlenschlæger (2000). The latter demonstrated a climate warming at the beginning of the medieval period at around A.D. 1020. Hydrographic measurements in Disko Bugt show that relatively low (< 34‰) salinities prevail in the upper *c.* 150 m of the water column (Lloyd *et al.* 1999). A much thicker low-salinity surface layer due to meltwater discharge is found in the fjords around Disko Bugt (Fig. 2) .

As raised beaches and archaeological sites of palaeo-Eskimo cultures are abundant around Disko Bugt, these

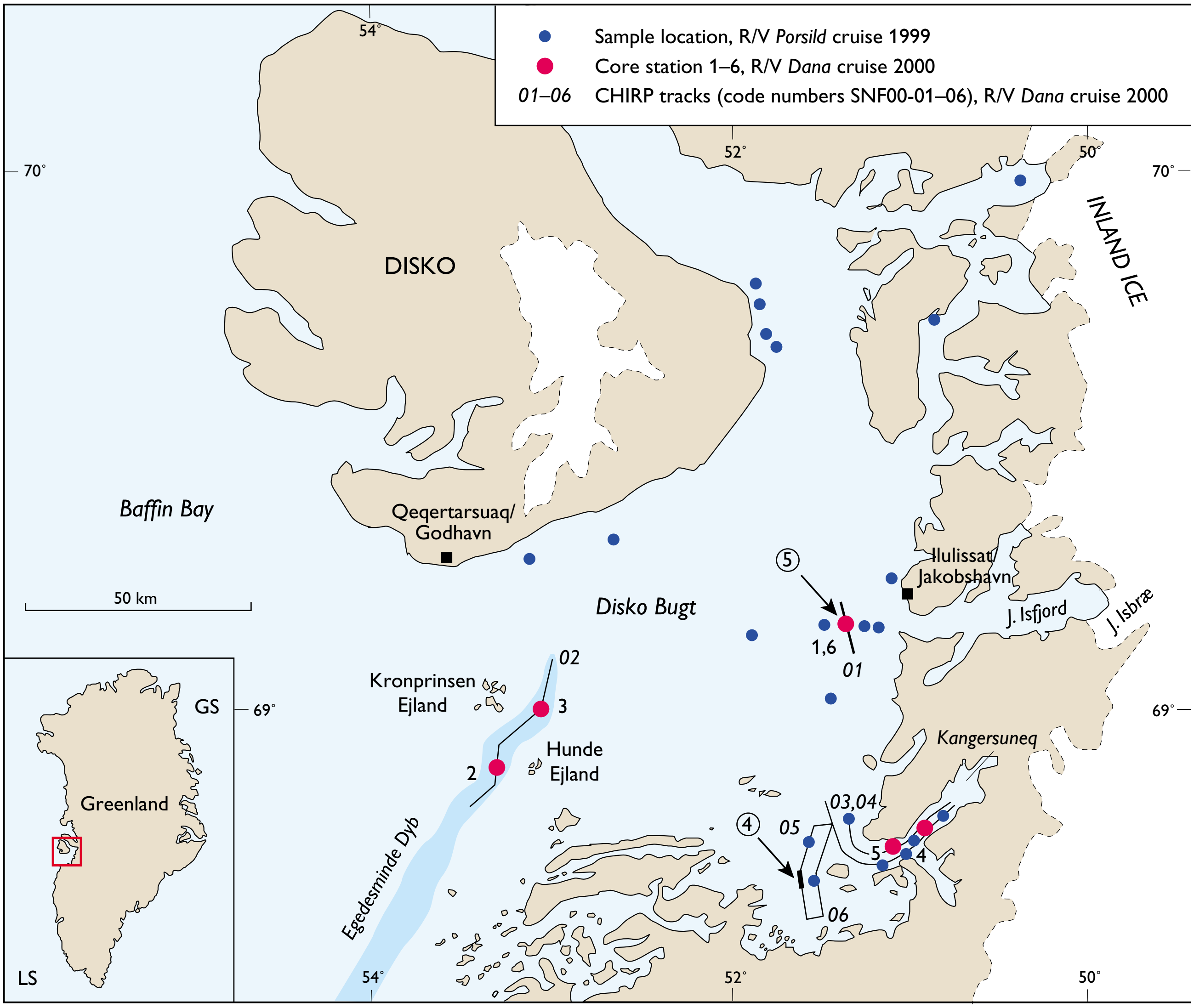

Fig. 1. Location of the sediment coring stations and CHIRP sub-bottom profiling tracks in Disko Bugt 1999 and 2000. The tracks SNF00-01–SNF00-06 have been abbreviated to 01, 02, etc. The coring stations 1 to 6 (DA00_0 code omitted) are indicated by **large red dots**, while smaller, unlabelled **dark blue dots** show the position of the hydrographic and sediment sampling stations occupied during the cruise with R/V *Porsild* in 1999. Coring stations 4 and 5 are located in the fjord Kangersuneq, where hydrographic measurements and other work were carried out in 1999 (see Fig. 2). ***J. Isfjord***: Jakobshavn Isfjord; ***J. Isbræ***: Jakobshavn Isbræ; **GS**: Greenland Sea; **LS**: Labrador Sea. The **labelled arrows** indicate: (**4**) the location of the CHIRP record illustrated in Fig. 4; and (**5**) the position of the piston core DA00-06 of which GEOTEK logging profiles are shown in Fig. 5.

onshore areas have been the subject of a large number of studies dealing with relative sea-level changes and glacio-isostatic adjustment. Moreover, Jakobshavn Isbræ, which is the fastest moving tidally controlled glacier in the world (Clarke & Echelmeyer 1996), has been the subject of numerous studies dealing with ice margin fluctuations since the last glaciation. It is generally believed that the ice sheet retreated from the shelf in two stages (Funder & Hansen 1996). After a first rapid retreat, the later deglaciation stage was much slower to reach its maximum position inland, i.e. > 15 km behind the present margin, in mid-Holocene times (Weidick *et al.* 1990). At the beginning of the Neoglaciation, around 4000 B.P., the Inland Ice readvanced, and at the end of the Little Ice Age (LIA) Jakobshavn Isbræ attained its maximum extension with a frontal position about 25 km west of its present margin (Weidick 1992). Regional sea-level changes, possibly related to a crustal response to Neoglaciation, have been reported by Rasch & Jensen (1997) and Long *et al.*

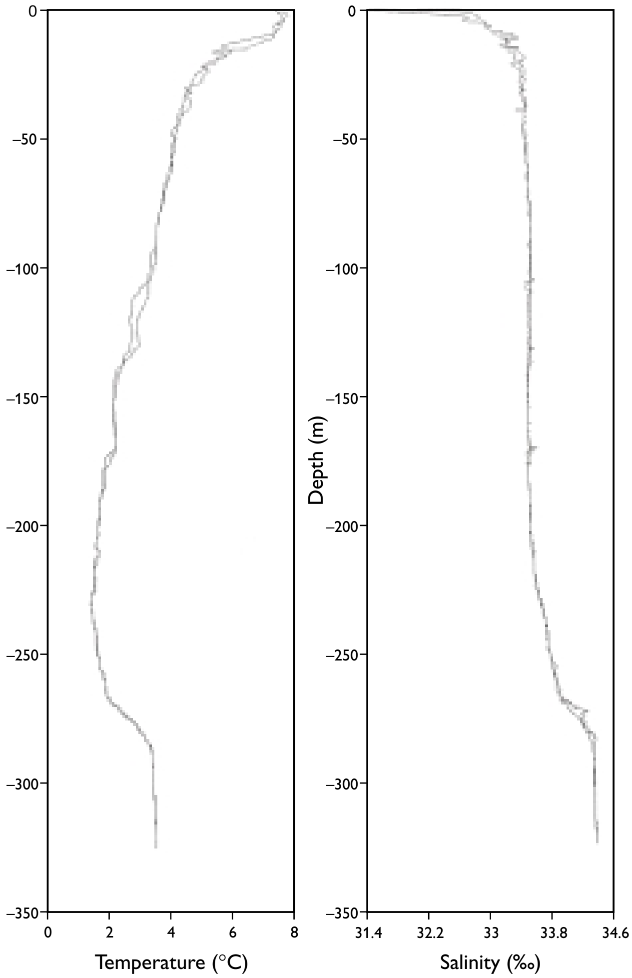

Fig. 2. *CTD* (conductivity/temperature/depth) profile illustrating temperature and salinity (conductivity) in the fjord Kangersuneq near the site of the cores DA00-04 and -05. The profiles show the presence of a thick (*c.* 275 m) low-salinity meltwater layer overlying saline bottom waters from Disko Bugt. Each diagram displays two profiles showing minor, fine-scale differences in temperature and salinity measured by the probe on its way to and from the bottom.

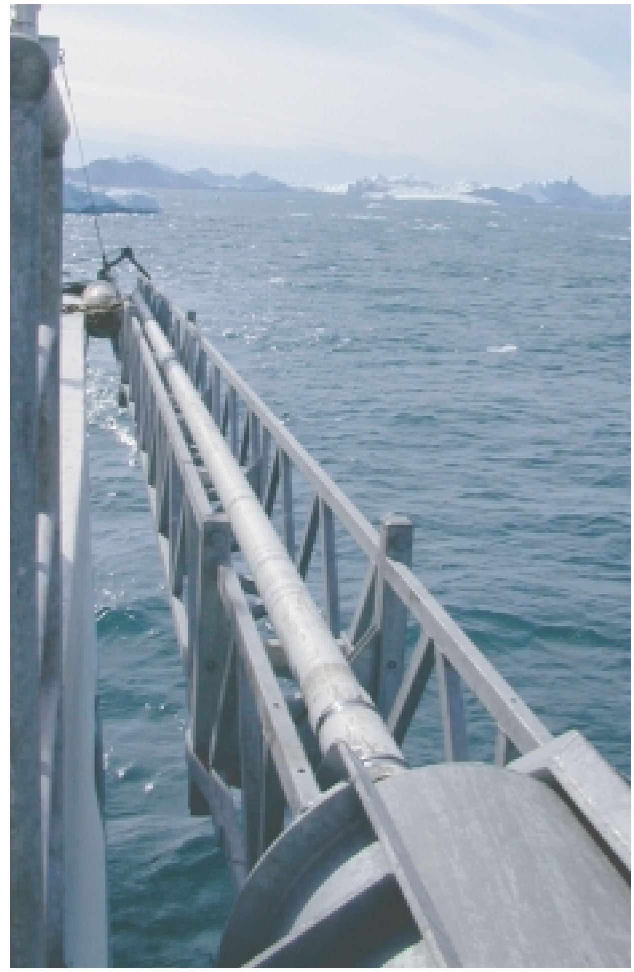

Fig. 3. The outboard cradle on R/V *Dana* with the 12 m piston corer, near the coring site off Jakobshavn Isfjord. Photo: John Boserup.

(1999). Studies on the south-east coast of Disko have demonstrated 3–4 transgressional stages within the past 2500 years, with the latest having occurred around the 14th–15th and 16th–17th centuries (Rasch & Nielsen 1995).

Work at sea – R/V *Dana*

With ice-sheet dynamics and their relationship to ocean climate as underlying rationale, the present study primarily focuses on the eastern part of Disko Bugt. Prior to the 1999 *Porsild* cruise, archive seismic data from the Westmar Project (Brett & Zarudzki 1979) had been studied for selecting potential (shallow) coring sites. From this pre-cruise archive study it appeared that relatively large accumulation areas of late glacial and Holocene sediments are mainly found in the easternmost part of Disko Bugt. One exception to this is the north-easterly extension of the Egedesminde Dyb in western Disko Bugt (Fig. 1). The archive seismic data indicate the presence of a > 200 ms TWT (Two-Way Travel Time) thick infill of presumed glaciomarine and younger sediments in the channel. Additional seabed data acquired with R/V *Porsild* in 1999 in the area off Jakobshavn Isfjord had yielded further evidence of a large sediment sheet or fan west and north of the mouth of this fjord. Preliminary results of accelerated mass-spectrometry (AMS) ^{14}C datings of the short cores from this location (J.M.L., unpublished data) indicate a clear decrease of the sedimentation

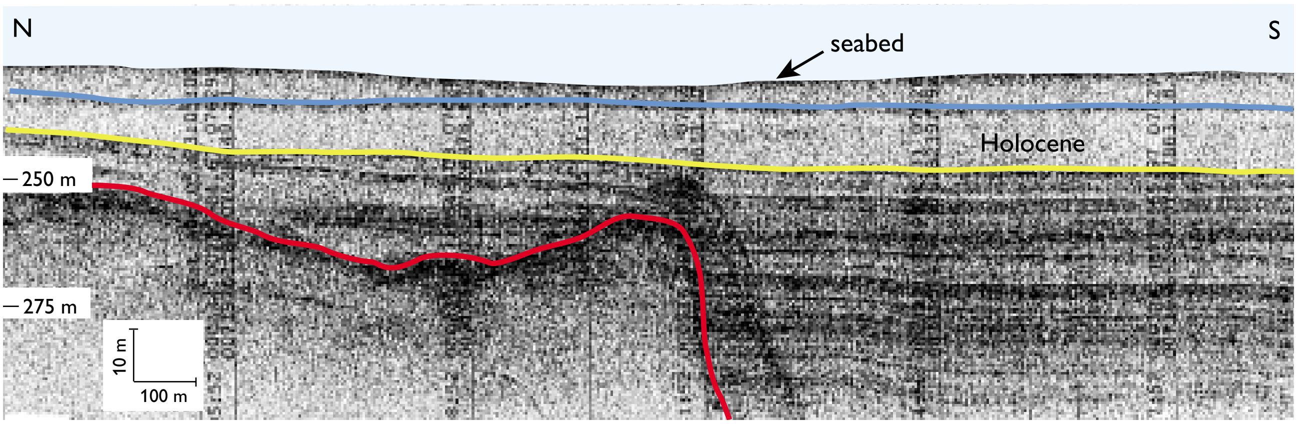

Fig. 4. CHIRP record from south-eastern Disko Bugt showing the northern, marginal zone of a large sedimentary basin, with an upper unit of presumed Holocene age divided into two parts by a reflector (**blue line**), overlying a thick, acoustically laminated sequence of late Pleistocene to early Holocene age. The top of the latter sequence is indicated by the **yellow line**, while the **red line** shows the top of the moraine. The location on line 05 is indicated by an arrow (**4**) in Fig. 1.

rates in a direction away from the mouth of the fjord. During the same cruise in south-easternmost Disko Bugt and adjacent fjord system, indications of a large depositional fan and basin had been found.

During the cruise of R/V *Dana* in 2000, first priority was given to collection of a long core from the immediate vicinity of the ice margin at the mouth of Jakobshavn Isfjord (Fig. 3) in order to obtain a sedimentary record of the history of Jakobshavn Isbræ. The ice conditions in August 2000 were, however, less favourable than in 1999, and consequently the coring site (Fig. 1, station 1/6) had to be located somewhat further away from the mouth of the fjord. (Note that the station codes 1 to 6 on Fig. 1 refer to the full core numbers DA00-01 to DA00-06.) For coring, a newly acquired 12 m piston corer with an inner liner diameter of 9.8 cm was used. The corer (total weight nearly 2 tons) was deployed with the help of a cradle along the port side of the vessel (Fig. 3), and coring was carried out using the port side trawl winch and its (20 mm) steel cable. For surface sediment sampling a Jonasson box-corer developed at Gothenburg University, Sweden, was used. In total five stations were occupied (Fig. 1) and the piston cores collected had lengths ranging from 8.90 to 11.20 m. Due to the presence of coarse ice-rafted debris causing coring failure at the first attempt, the station off Jakobshavn Isfjord had to be occupied twice (station 1/6). Intensive degassing with sediment blowing out from the corer during retrieval demonstrated the presence of large amounts of shallow gas in sediments from the deep-water stations 2 and 3 located in Egedesminde Dyb.

In addition to coring, shallow seismic sub-bottom information was obtained with a Datasonics CHIRP (2–10 kHz) acoustic profiling system. The 38 kHz (Simrad) hull-mounted echo sounder of R/V *Dana* was used for analogue bathymetric recording. The CHIRP sub-bottom profiling tracks were run in all areas where cores were taken (Fig. 1), and in addition in the south-easternmost part of Disko Bugt. The CHIRP data from the latter area indicate the presence of a large sedimentary basin and provide acoustic evidence of marked changes in late Quaternary depositional conditions (Fig. 4). The Holocene, assumed to be acoustically characterised by the uppermost, transparent unit shown on the CHIRP record, also yields evidence of a change in the sedimentary regime. This is concluded from the presence of a distinct reflector which divides the transparent unit into two parts. Moreover, in the adjacent area to the north, faulting in late Quaternary sediments indicates neotectonic activity possibly related to glacio-isostatic adjustment of the area.

Post-cruise core studies and preliminary results

Prior to opening of the cores, all core sections were logged using either a Bartington MS2 device for measuring magnetic susceptibility (cores DA00-02, -04), or the GEOTEK multi-sensor core-logger of the Baltic Sea Research Institute in Warnemünde, Germany. The latter instrument produces core logs for magnetic susceptibility (MS), GRAPE (gamma ray attenuation porosity

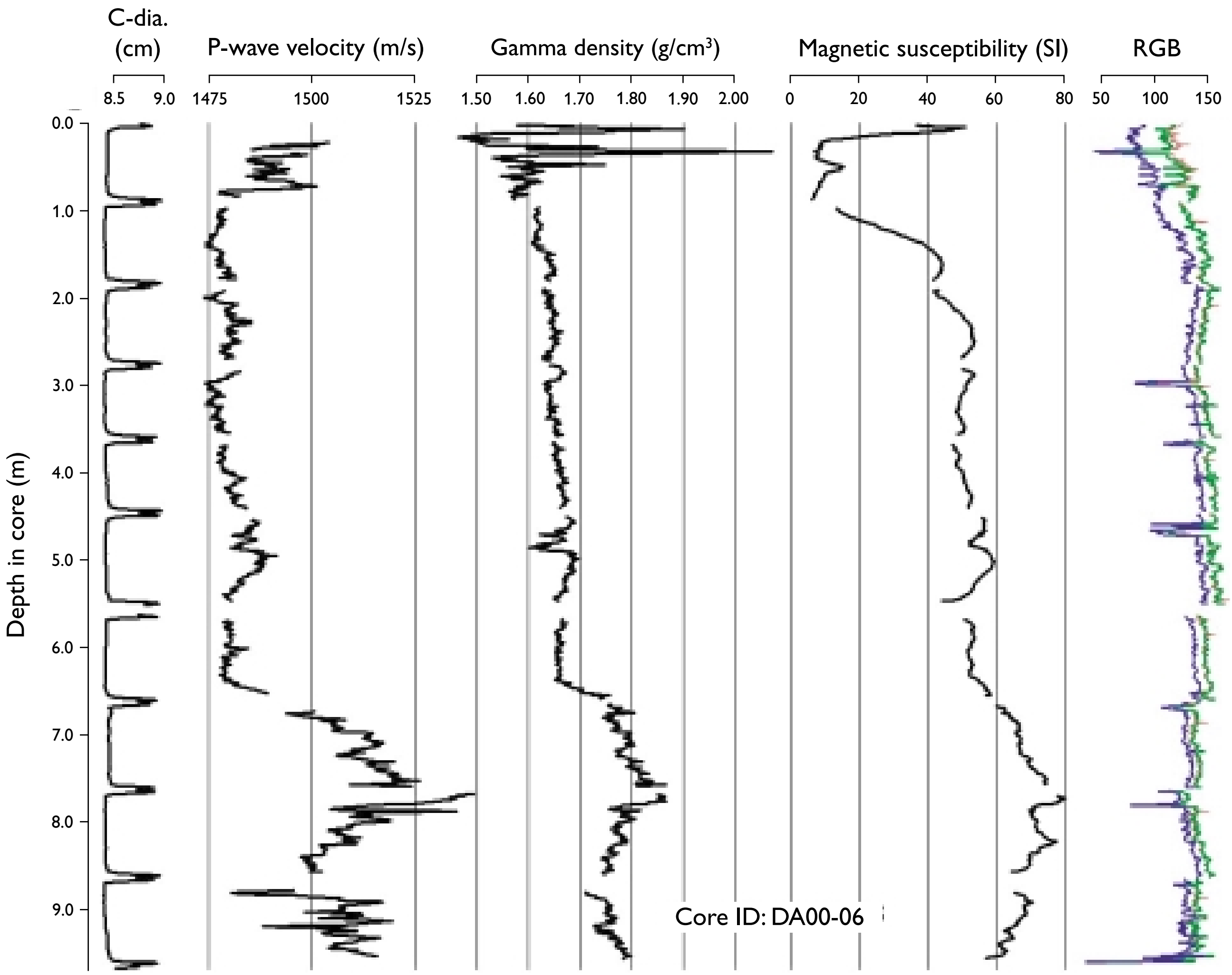

Fig. 5. GEOTEK logs for core DA00-06 taken off Jakobshavn Isfjord. Location is shown by arrow (**5**) in Fig. 1. The figure shows the down-core variation of P-wave velocity, GRAPE gamma-ray density, magnetic susceptibility and the **RGB** (Red/Green/Blue) colour scanning data. **C-dia**: Core diameter.

evaluator) density, P-wave velocity, and the RGB (Red/Green/Blue) digital colour scale. The GEOTEK results for core DA00-06 are illustrated in Fig. 5. After logging, the cores were opened, visually inspected, and described. Subsampling was carried out for AMS ^{14}C dating, magnetic and mineralogical analyses, grain-size determination, and micropalaeontological studies including foraminifera (Durham University, UK), diatoms and dinoflagellates. Using the surface sediment samples from the 1999 R/V *Porsild* cruise, a reference base for palaeo-oceanographic reconstruction based on the actual microflora and fauna is about to be completed.

The core data shown in Fig. 5 provide evidence for two major changes in the sedimentary environment off Jakobshavn Isfjord. These occur at around 1.0 m depth, and more gradually between 6.5 m and 7.0 m core depth. From visual inspection of the core, only the distinct change at around 1.0 m depth is obvious. At this depth a transition is seen from more mottled and bioturbated (light) olive-grey sandy mud with coarse ice-rafted debris (gravel, pebbles) at the top of the core to mainly homogeneous grey mud with some silt and very fine sand below, notably without coarse ice-rafted debris. This lithological change can be interpreted to reflect the transition from mainly open water conditions during summer to a subglacial situation with a floating glacier over the site. Moreover, we assume that the latter conditions were characterised by a virtual absence of warmer, saline (Baffin Bay) bottom water (see Fig. 2), resulting in very low bottom melting rates and consequently almost no ice-rafting. This hypothesis will be tested by foraminiferal (L.A.P.) and diatom analyses currently being undertaken. The deeper level, more gradual change is illustrated by higher MS, density and P-wave velocity, and can probably be related to a general slight increase of grain size and/or different mineral input. This is tentatively attributed to the stronger influence of Jakobshavn Isbræ on near-bottom sediment transport and deposition, as would be expected with increased glacier thickness at an early deglaciation stage.

The two cores DA00-04 and -05 taken in the fjord Kangersuneq in south-easternmost Disko Bugt (Fig. 1) demonstrate a marked difference in sedimentation rates between the two sites. This is not unexpected, as echo sounder profiling during the earlier R/V *Porsild* cruise in 1999 had revealed the presence of two sedimentary basins at different water depths, separated by an interpreted moraine ridge. The lithology of the easternmost core DA00-04 suggests sedimentation rates that are markedly lower than those found in core DA00-05. This conclusion is based on a change at mid-core depth in core DA00-04 which shows a transition from bioturbated (light) olive-grey silty mud to homogeneous, mainly grey silty mud with occasional sand stringers. The latter lithology is concluded to be indicative of a subglacial or proximal ice-margin environment with low bottom melting rates, as coarse ice-rafted material is virtually absent. The core DA00-05 contains bioturbated sediment throughout the core, and its sediment is comparable with the sediment type of the upper part of core DA00-04. This suggests a depositional environment with continuous advection of well-ventilated (saline) bottom water from Disko Bugt (Baffin Bay) and the absence of a permanent ice cover.

The lithologies of the cores DA00-02 and -03 taken from Egedesminde Dyb show a non-oxic sub-bottom environment below an oxidised, 2–3 cm thick surface layer. This is in contrast to observations in the other cores, in which sediments appear to be oxic. The sediments retrieved from Egedesminde Dyb are mottled and burrowed silty clays. Noteworthy are 2–4 cm thick, rhythmically alternating lighter and darker coloured intervals particularly seen in the lower part of the cores. As noted above, a very high gas content was observed in the cores. Due to gas expansion during retrieval, the sediment column of core DA00-03 was disrupted and it shows large, up to 0.5 m long, void intervals. Otherwise, the sedimentary structures appear intact, and no disturbance due to the piston coring process was observed. Intact sedimentary structures suggest that gas hydrates are not likely to occur in the sediments cored; if present these would have caused disturbance of the internal sediment bedding.

Prior to opening of core DA00-02, pore water and gas were sampled from the core with a syringe, and large intact sediment samples were taken for pore water and solid phase organic matter analyses. The analysis of the syringe gas sample shows the presence of shallow gas with an elevated (22.2%) methane content, and only traces (*c.* 1 ppm) of propane and pentane. The measured pore water chlorinity values deviate only little from that of normal marine sediment pore water, which confirms that significant volumes of gas hydrates are unlikely to occur at the surface or in shallow sub-seabed sediments of Egedesminde Dyb. Formation of significant amounts of gas hydrates alter pore-water chlorinity, as the water fixed in hydrates is less saline. Thus, the shallow gas may be formed either *in situ* from the accumulation of marine organic matter, or may originate from seepage from depths where conditions within the relatively thick (> 200 ms TWT) post-glacial sedimentary sequence may have been particularly favourable for gas formation. The results meanwhile obtained for the solid phase organic matter content of core DA00-02, which show organic carbon contents of about 2%, clearly point to *in situ* formation as a likely source of the gas.

Concluding remarks

It can be concluded that several cores collected during the R/V *Dana* cruise in 2000 have the potential to provide high-resolution records of Holocene palaeo-oceanographic changes in Disko Bugt (cores DA00-02, -03, -05). Moreover, core DA00-05 collected in the fjord Kangersuneq may also yield information on terrestrial environmental changes, as for example variations in freshwater discharge. In addition, diagenesis related to the formation of shallow gas is a specific issue which can be studied in cores from Egedesminde Dyb. Preliminary geochemical analyses suggest a mainly *in situ* origin of the gas found in the shallow sub-seabed sediments of this area. This finding does not, however, exclude the possible presence of gas hydrates at greater sub-seabed depth.

The cores DA00-04 and DA00-06 both display a sedimentary record which appears to provide important information on the deglaciation history of the Inland Ice of West Greenland.

The shallow seismic data obtained during the R/V *Dana* cruise, as well as the echo sounding and shallow-core data from the 1999 R/V *Porsild* cruise, have shown that future collection of long piston cores at several other sites could further contribute to better understanding of the postglacial development of the area.

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Palaeolimnological investigation of atmospheric pollution in the Søndre Strømfjord region, southern West Greenland: accumulation rates and spatial patterns

Richard Bindler, N. John Anderson, Ingemar Renberg and Carola Malmquist

High-latitude ecosystems are inherently sensitive to natural environmental stress as a result of extreme seasonal variations in light and temperature, nutrient limitations, as well as other physical and chemical characteristics; consequently, these regions are quite vulnerable to the addition of pollutant stress. There is a poor understanding of spatial and temporal patterns of atmospheric pollution in the Arctic, because of the lack of monitoring stations and networks for current and past atmospheric deposition. Today, however, the Arctic is recognised as an important focus for long-range transport of contaminants, particularly from strong air flows which carry airborne pollutants from industrial regions at lower latitudes, e.g. heavy metals and persistent organic pollutants (POPs). A diverse range of anthropogenic pollutants has been shown to be present across much of the region (Aarkrog *et al.* 1997; AMAP 1998). Of particular importance are compounds, such as mercury and POPs, which present a risk to native fauna and also inhabitants. It is hypothesised for some volatile organic compounds, as well as possibly for mercury, that there may be a latitudinal fractionation that contributes to the continued mobilisation of these compounds from warmer to colder climates, where they are ultimately deposited and stored (Wania & Mackay 1993). Experimental data and limited field research support this 'cold-condensation' hypothesis, at least for some POPs (Blais *et al.* 1998).

Many areas of the Arctic, especially Greenland, are poorly represented in the scattered sampling programs that have so far been undertaken. Time-series data are even more limited, resulting in great uncertainty over the temporal trends of environmental contamination. A specific gap identified in arctic research is the lack of

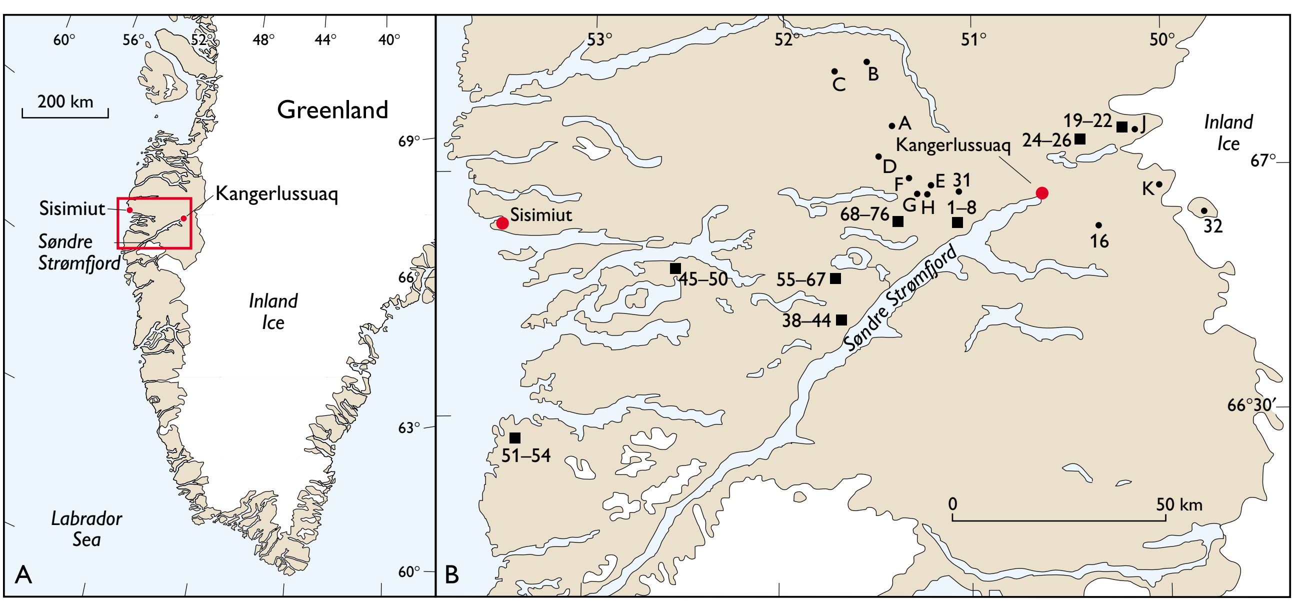

Fig. 1. **A**: Location of the Søndre Strømfjord region, southern West Greenland. **B**: The study lakes east and west of Kangerlussuaq cored in May 2000 are indicated by letters (**A–H** and **J**, **K**). Numbered lakes and groups of lakes refer to previously sampled lakes (Anderson *et al.* 1999), from which sediment samples were included in the analyses (• = individual lake; ■ = group of lakes).

Geology of Greenland Survey Bulletin 189, 48–53 (2001)

long-term retrospective time trends. A particular weakness in studies of time trends is the general assumption that natural, non-polluted conditions existed prior to the mid-1800s. Analyses of lake sediments and peat deposits in Europe (Renberg *et al.* 1994, 2000; Shotyk *et al.* 1998; Brännvall *et al.* 1999) and Greenland ice cores (Hong *et al.* 1994) have revealed an approximately 3500-year history for lead (Pb) pollution in the northern hemisphere, which contradicts the assumption of the mid-1800s representing 'background' levels.

In Greenland, studies of pollutants in the ice-free terrestrial margin have focused largely on synoptic surveys to identify and quantify pollutants in the contemporary environment. Temporal changes in pollutant deposition and accumulation in the terrestrial environment are not well established. Lake sediments provide an ideal archive to examine many anthropogenic environmental pollutants, as well as to assess the range of natural variability of compounds or elements such as lead and mercury. The Søndre Strømfjord region (Fig. 1) offers excellent opportunities for palaeolimnological research because of the lack of cultural disturbance and, more importantly, because of the extensive availability of data from limnological and palaeolimnological research programs that have been carried out in the region since 1996 (Anderson *et al.* 1999).

The long SW–NE-trending fjord around which this study is centred is known by both the Danish name, Søndre Strømfjord and the Greenlandic name, Kangerlussuaq. In this paper we follow the convention of using 'Søndre Strømfjord' for the fjord and 'Kangerlussuaq' for the airport at the head of the fjord (Fig. 1).

Main aims

The aims of the present project in the Søndre Strømfjord region of southern West Greenland (Fig. 1) are to:

1. Assess the onset of mercury and lead pollution and their accumulation rates in selected lake sediments.
2. Assess the spatial patterns and enrichment rates of mercury and lead pollution in sediments of lakes along a west to east transect in the Søndre Strømfjord region employing surface and bottom samples from short cores of recent sediments (*c.* 15–35 cm in length).
3. Supplement archived sediment samples with the collection of new lake sediment cores along an altitudinal transect (*c.* 150 to 950 m above sea level) and in lakes adjacent to the ice margin to assess the hypothesis of 'cold condensation', i.e. the progressive revolatilisation of organic pollutants from warmer to colder climates.
4. Establish which persistent organic pollutants (POPs) are present in recent lake sediments and assess temporal changes in their accumulation.

In the case of the first two aims, sediment samples collected in previous field campaigns during 1996–1999 can be used. Field work in 2000 was initiated specifically to collect fresh sediment samples for POP analyses and to address the 'cold condensation' hypothesis.

Temporal changes in atmospheric pollutants

Analysis of lake sediment cores is a useful method of documenting the historical loading of atmospheric pollutants to remote areas, such as mercury, lead and organic pollutants. These pollutants derive from the combined effects of direct deposition to the lake surface and run-off from the catchment area. Palaeolimnological researchers have used lake sediments to reconstruct site-specific as well as regional pollution histories in order to determine the onset of atmospheric pollution, the rates

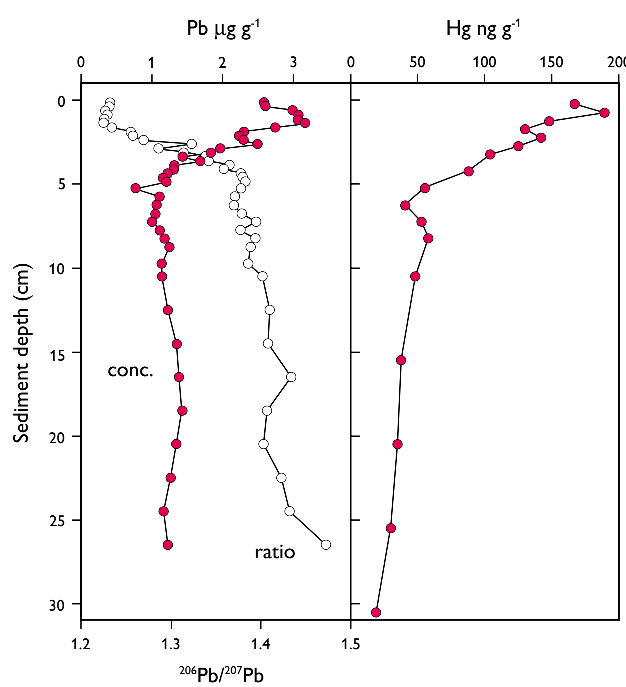

Fig. 2. Profiles of lead (Pb concentrations and $^{206}Pb/^{207}Pb$) and mercury (Hg) in sediment cores from Lake 32 (Nunatak lake) (Bindler *et al.* 2001a, b).

of increase of individual pollutants and spatial patterns of deposition. Landers *et al.* (1998) summarised the most reliable mercury reconstructions from lake sediment cores from arctic and boreal ecosystems to evaluate spatial patterns at high latitudes on a broad scale.

Analyses of mercury and lead in ^{210}Pb-dated cores from a few lakes in the Søndre Strømfjord area (Lakes 16, 32, 53 and 70) show patterns generally consistent with data from elsewhere in the Arctic and the boreal zones. Cores from all four lakes show clear evidence of pollution from industrial sources, with enhanced lead and mercury concentrations and accumulation rates in near surface sediments relative to deeper sediments (Fig. 2). In the case of mercury, analysed using cold vapour atomic fluorescence spectrometry (CVAFS), the sediment records indicate increased mercury accumulations of about two to three times that determined for background sediment layers (Bindler *et al.* 2001b). The current and historic mercury accumulation rates in the Greenland lakes are in the same range as those reported for lakes from the Canadian Arctic, where comparable lakes had mercury accumulation rates of 1–5 µg m^{-2} yr^{-1} in deeper sediments, which increased to 5–8 µg m^{-2} yr^{-1} in surface sediments (Landers *et al.* 1998). The Greenland sediments indicate an initial increase in the mercury accumulation rate during the mid-1800s (Bindler *et al.* 2001a), which is generally consistent with the onset of mercury pollution in North America and northern Europe. In one lake (Lake 32; Fig. 2), located on a nunatak *c.* 5 km within the ice margin, there is an indication of a slightly earlier mercury pollution signal, prior to 1800, based on extrapolation of the ^{210}Pb chronology (Bindler *et al.* 2001b).

For lead, analyses of the sediment cores in lakes around Søndre Strømfjord also included stable lead isotopes (^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb). Lead isotopes make it possible to infer the provenance of the pollution lead in the environment, based on the fact that lead ores have characteristic lead isotopic compositions that are typically distinct from the isotopic compositions of soils and bedrock. Consequently, isotope analyses have become an effective method in environmental studies to quantify pollution lead contributions and to infer specific sources for the pollution lead. For the sediment cores from the Søndre Strømfjord region, there is a large decline in the ^{206}Pb/^{207}Pb ratio coincident with increased lead concentrations upwards in the cores (Fig. 2) clearly indicating that the increased concentrations are a direct result of an increasing input of pollution lead to these lakes (Bindler *et al.* 2001b). Based on an isotope mixing model, the lead pollution can be demonstrated to derive from western Europe and Russia, and not from North America (Bindler *et al.* 2001b).

Spatial patterns of Hg and Pb pollution

Analyses of sediment samples from earlier field campaigns in the Søndre Strømfjord region (individual lakes and lake groups numbered in Fig. 1) revealed some trends on the spatial pattern of atmospheric pollution. These samples represented the top (0–1 cm) and bottom (a 1 cm interval at *c.* 15–35 cm depth) of gravity cores from lakes north of Søndre Strømfjord. As expected from the steep gradient for annual precipitation, with the highest annual precipitation at the coast and declining rates inland, the unsupported ^{210}Pb fluxes and inventories in the lake sediments were higher at the coast and lower inland (Bindler *et al.* 2001b). Predictably, pollution lead inventories followed a similar pattern: higher lead concentrations and a stronger influence on the isotope composition by pollution sources on the surface lake sediments nearer to the coast together with larger pollution lead inventories in whole cores (i.e. the total amount of pollution lead accumulated in the sediment core). The close relationship between the gradient for ^{210}Pb fluxes and pollution lead inventories supports the inference that the differences between sites is largely due to variations in rainfall.

In contrast, the mercury analyses of the lake sediments, both cores and the top/bottom sample pairs, revealed an unexpected reverse trend. While the sediments generally revealed a two- to three-fold enrichment for mercury in surface sediments relative to the deeper sample, there was a tendency towards greater enrichments in the vicinity of the ice margin (Bindler *et al.* 2001a). The lakes within about 20 km of the ice-sheet margin had higher mercury concentration enrichments, from three to as much as ten times greater than the background concentration. This region corresponds approximately with the area most influenced by the meteorology of the ice margin, e.g. the katabatic winds that flow down off the ice and over the adjacent tundra, and suggests the possibility of a ‘cold condensation’ effect on mercury contents.

Field work in 2000

During May 2000, sediment cores were collected from eleven lakes in two areas around Kangerlussuaq. Sediment cores were collected with a gravity corer. One

Fig. 3. Sampling at Lake H in May 2000. The lake is at *c.* 150 m a.s.l., well below the snowline.

area (Lakes A–H on Fig. 1; ~ 67°10′N, 57°30′W) constituted a 35 km long transect of eight lakes along an elevation gradient from *c.* 150 m to 950 m above sea level. A second group of three lakes (a new core from Lake 21 and new Lakes J and K) were each located within a few km of the ice-sheet margin, east of Kangerlussuaq. One lake (Lake K, 67°02.6′N, 50°09.9′W) is situated immediately above an ice tongue whose meltwater drains into the head of Søndre Strømfjord.

At each lake, two to three short sediment cores were collected and sectioned in the field. One core was sectioned into 1 cm intervals and stored in glass containers for the analysis of persistent organic pollutants. A second core was sectioned into a surface sediment sample (0–1 cm), a bulk sample (9–10 cm), and a bottom 2 cm interval taken near the base of the core (the cores were *c.* 20–30 cm in length). In most lakes a third core was collected and sectioned into 0.5 cm slices from 0–10 cm, and 1 cm slices down to the base of the core, for detailed stratigraphic analyses of mercury and lead. To make assessments of bulk pollution, the background concentrations (the concentration at depth of the compound of interest, e.g. mercury) were subtracted from the concentrations in the surface and bulk samples. Mercury pollution inventories (mass per unit area) can then be compared between sites, and their differences assessed in light of the altitude of the lakes.

The eight lakes west of Kangerlussuaq (A–H) were selected as an altitudinal substitution for a climatic gradient, and to limit regional variations in geology and precipitation as much as possible. The use of this altitude-for-climate substitution can be illustrated by the situation in May 2000; the snowline was at *c.* 500 m above sea level, such that one lake was situated at the snowline, two well above and the remaining five lakes below the snowline (Fig. 3). Two of the lower elevation lakes were found to have laminated sediments and high conductivities, similar to other studied lakes in the area at the head of the fjord (Anderson *et al.* 1999).

The sediments from the second group of lakes (21, J and K) east of Kangerlussuaq were sampled to further assess the 'ice-margin' effect (Bindler *et al.* 2001a). Lake K is adjacent to the margin of the Inland Ice, while Lakes 21 and J are within 5 km. Studies of meteorological conditions at the Inland Ice margin during the Greenland Ice Margin Experiment (GIMEX) in June and July 1991 observed that the energy balance at the margin was strongly influenced by the radiative differences of the ice and the adjacent tundra (Fig. 4; Duynkerke & van den Broeke 1994). The temperature gradient from the ice to tundra in the summer produces strong katabatic winds that flow down off the ice sheet and out over the tundra. The region most strongly affected by this thermal forcing coincides geographically with the lakes that showed the highest mercury enrichments. Detailed stratigraphic analyses from the new study lakes will complement the analyses of archived samples.

Initial results of high-resolution gas chromatography/mass spectrometry (HR GC/MS) analyses of the lake sediments indicate low concentrations for polychlorinated biphenyls (PCBs) (*c.* 0.5–3 nanogram g^{-1} for total PCBs; individual compounds are measured at picogram g^{-1} levels) that are consistent with other regions of the Arctic (e.g. northern Canada). However, analy-

Fig. 4. The region along the ice margin (as here north-west of Kangerlussuaq) is strongly affected by the radiative differences of the glacier and the adjacent tundra (Duynkerke & van den Broeke 1994), which may influence processes that affect mercury accumulation and retention in lakes in this region. Air temperatures above the surface of the Inland Ice in the background of the photograph are just above freezing in the summer, whereas temperatures above the adjacent tundra (foreground) may reach 15°C. It is this temperature gradient that periodically gives rise to strong katabatic winds flowing from east (the ice) to west (the land). As described in the text, these strong environmental (temperature, radiation) gradients from ice to land may influence mercury accumulation and retention in the lakes on the tundra. The lake in the middle foreground is *c.* 250 m across.

ses of some sediments, particularly from the lakes with laminated sediments and high-water conductivities, have been complicated by the high sulphur contents which necessitated pre-treatments. Additional improvements in these procedures have contributed to a lowering of the detection limit for persistent organic pollutants in sediment samples and reductions in sample size, which permits better temporal resolution in sediment cores. Assessment of analyses of the samples collected in May 2000 are in progress, which includes estimations of accumulation rates and cumulative inventories of PCBs and polybrominated diphenyl ethers (PBDEs), a class of widely used flame retardants. The results of the sampling in Greenland in May 2000 will be compared with those of a similar project using lake sediment cores taken in the northern Swedish mountains.

Conclusions

Ongoing research on the limnology and palaeolimnology of lakes in the Søndre Strømfjord region, which is focused largely on aspects related to climate change, has provided a solid foundation for additional studies on environmental change, such as assessments of pollution inputs. In addition to contributing to the general understanding of the distribution of pollutants in the Arctic, both in terms of the rates of deposition and their spatial distribution, analyses of lake sediments in the Søndre Strømfjord region also provide a potential for assessing climatic processes that may interact with pollutant deposition and accumulation; such as the 'cold condensation' hypothesis, which contributes to the continued mobilisation of volatile compounds to the Arctic.

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Determining the date of ice-melt for low Arctic lakes along Søndre Strømfjord, southern West Greenland

N. John Anderson and Klaus P. Brodersen

The length of ice cover has considerable influence on the functioning of lake ecosystems, particularly so in continental and high-latitude regions where lakes freeze annually. Long-term trends in the length of ice cover and the date of ice break-up can be related to regional weather patterns, such as the North Atlantic Oscillation. It is this relationship to weather patterns that has generated considerable interest in the use of long-term ice-records as climate proxies. Although it is reasonable to assume a relationship between the length of the ice-free period and lake productivity, it is unclear if this relationship influences the sedimentary record. Whether these ice-climate interactions can be identified in the sediment record is important for distinguishing long-term palaeoclimatic trends from variations in the sediment record (Anderson *et al.* 2000).

In the high Arctic, ice cover is often nearly permanent from year to year and the extent of moating is important for biological processes. An ice remnant on a lake during one summer can increase water temperatures the following spring (Doran *et al.* 1996). This increased spring temperature is caused by the remnant ice trapping heat in the lake together with reduced convective cooling. As a consequence, this process reduces the likelihood of two consecutive years with residual ice. In the low Arctic, where low-altitude lakes are normally completely ice-free every summer, it is the timing of the spring ice-melt period and the total length of the ice-free period that can be important for biogeochemical processes. For example, the break-up of the ice is associated with emergence of chironomids and their mating (Brodersen *et al.* 2001, this volume) while prolonged ice-cover and anoxia will influence internal biogeochemical cycling of nutrients and alkalinity generation. The length of the ice cover period, coupled with the rapid development of thermal stratification is one

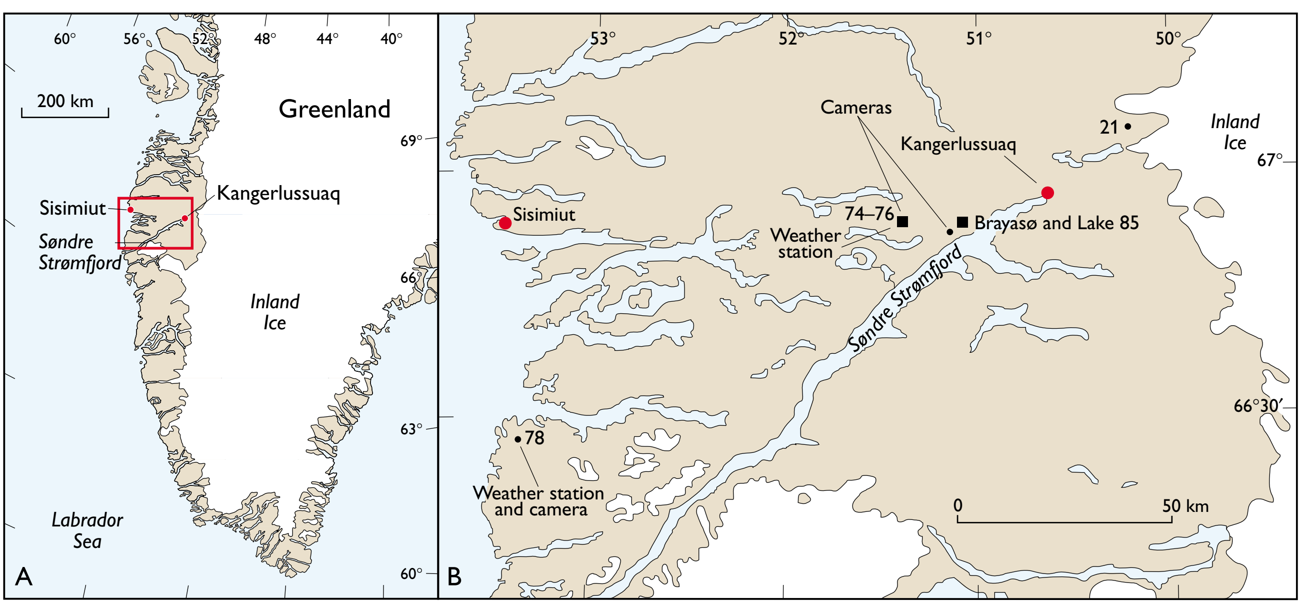


Fig. 1. **A**: The study area in southern West Greenland. **B**: The study area with location of cameras, automatic weather stations and lakes with thermistor chains. ■ = group of lakes; • = individual lake. Modified from Brodersen & Anderson (2000).

Geology of Greenland Survey Bulletin 189, 54–58 (2001)

of the reasons why so many lakes in southern West Greenland have laminated sediments (Anderson *et al.* 2000). At the regional scale the main factors governing the timing of ice-melt and the length of the ice-free period are radiation input and air temperature, altitude, lake area and volume.

There is considerable geographic and inter-annual variability in the length of ice-free period in lakes (freeze and break-up date). An analysis of all available data for time series over 100 years in length from lakes throughout the world has revealed a trend for freeze dates to have occurred 5.8 days later per 100 years and break-up date 6.5 days earlier per 100 years (Magnuson *et al.* 2000). Determining the date of ice break-up has traditionally been based on continuous field observations, some of which cover hundreds of years (e.g. Lake Suwa, Japan), recorded for cultural or religious as well as scientific reasons (Magnuson *et al.* 2000). However, there are very few data on ice-melt dates for remote lakes, such as the many thousands in the ice-free area of southern West Greenland. In this project, we follow the process of ice-melt to the date of final disappearance of ice (ice-out).

Recent sporadic field observations along Søndre Strømfjord by the authors indicate that ice-melt occurs earlier in those lakes closest to the head of the fjord, largely reflecting the climate gradient in this area (Hasholt & Søgaard 1976). At the coast, where the summers are cooler and fog banks reduce radiation input, lakes can still be completely ice covered with minimal moating, when ice-melt on the lakes close to the airport at Kangerlussuaq (Fig. 1) is nearly complete. Previous field work in this area (Anderson *et al.* 1999) also indicates substantial variation from year to year. For example, in 1998 lakes around the head of the fjord were largely ice-free by mid-June. The following year, 1999, when mean April–May temperatures were ~ 2°C lower than in 1998, ice-melt was still not complete by 1 July.

In this paper, and on Fig. 1, we follow the convention of referring to the fjord as Søndre Strømfjord and the airport at the head of the fjord as Kangerlussuaq; the fjord is also known by its Greenlandic name Kangerlussuaq.

Use of satellite imagery is useful and can cover large numbers of lakes, but its application can be limited by cloud cover, resolution – not all the smaller lakes in a given area are easily visible (Wynne *et al.* 1996) – and temporal coverage. As much palaeoclimate work is based on sediment records from small lake basins, this lack of information for smaller lakes can be problematical. It was decided, therefore, to attempt an alternative approach using automatic cameras and lake-water temperature dataloggers.

Field activities in 2000

The aim of field work in 2000 was to establish local monitoring systems that could be used to record the date of ice-out at locations along the climate gradient from the Inland Ice margin to the coast south of Sisimiut (Fig. 1). It was hoped that by assembling information

Fig. 2. Downloading data from the automatic weather station near Lake 78 on 29 August 2000. For location, see Fig. 1B.

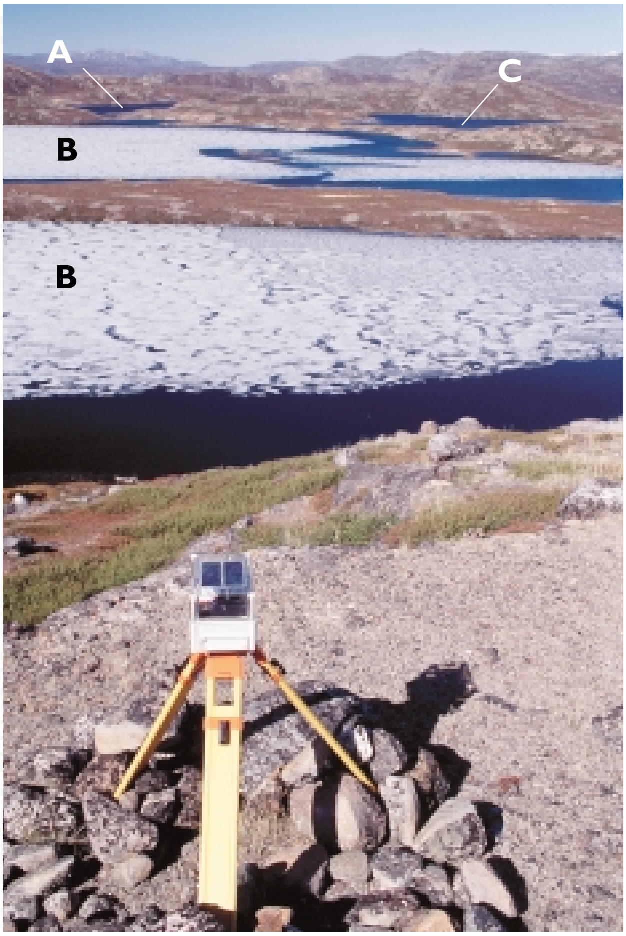


Fig. 3. Remote-controlled camera overlooking Lakes 74 (**A**), 75 (**B**) and 76 (**C**). The height of the camera and tripod is about 1.4 m.

about the date of ice-out and local meteorological conditions it would be possible to generate a simple empirical model that could be used to predict future ice-out dates.

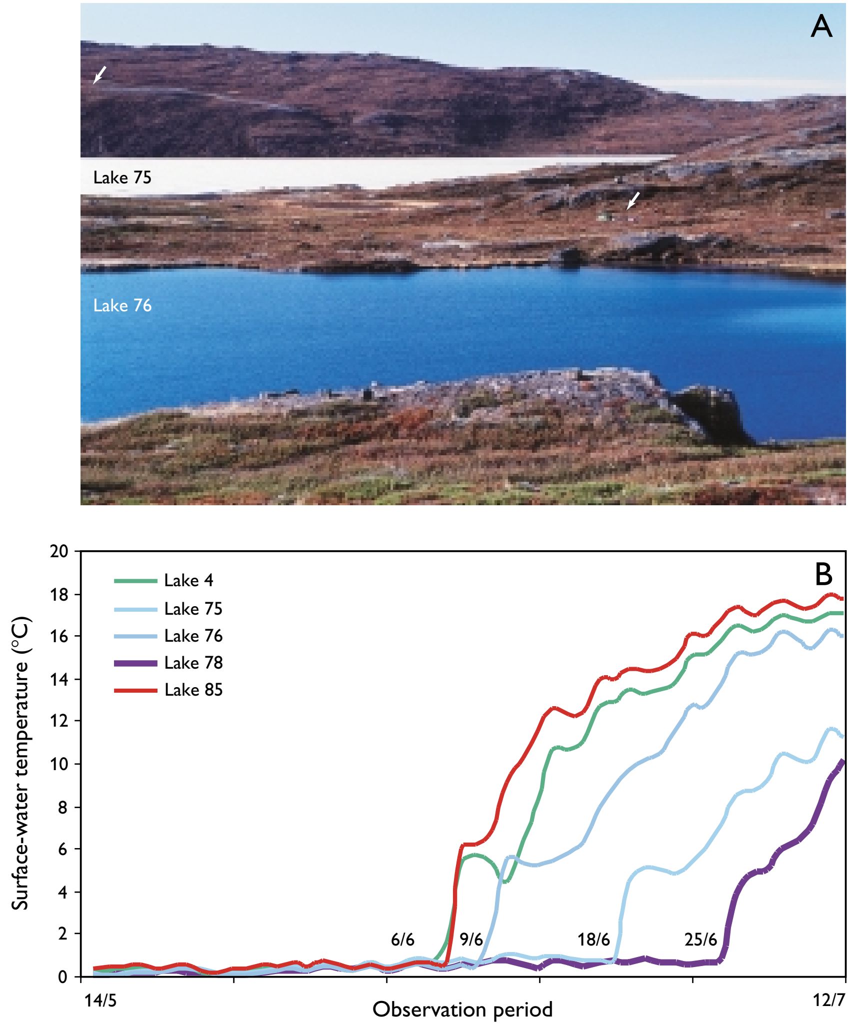
The study sites are spread along the climatic gradient (continental to more maritime) from the Inland Ice margin to the coast south of Sisimiut. Two lakes close to the head of the Søndre Strømfjord were sampled (Lake 4 = Brayasø and Lake 85) together with Lakes 75 and 76, approximately half way along the fjord. The most easterly site was Lake 21, and the most westerly, Lake 78 (Fig. 1B). The lakes cover an altitude range from 45 m to 470 m and vary in area from < 10 ha to ~ 140 ha. Maximum depths range from 14 to 50 m.

The main field work in 2000 took place between 23 April and 6 May and consisted of the deployment of thermistor chains (Brodersen & Anderson 2000), automatic weather stations and cameras. At five lakes (Lakes 4 = Brayasø, 22, 75, 76, 78; Fig. 1B) chains of thermistors were deployed (10–12 per lake depending on the maximum depth). Thermistors were set to record water temperature at hourly intervals. They were attached to steel wires to reduce the possibility of the ice cutting them and dropped through a hole cut in the ice. The automatic weather station (AWS) between Lakes 75 and 76 was upgraded (to measure solar radiation), and a similar system was erected adjacent to Lake 78 near the coast (Fig. 2). At three sites (Fig. 1B), an automatic digital camera was set up overlooking an individual lake (i.e. Lake 78) or groups of lakes (i.e. close to Brayasø and Lake 85, and overlooking Lakes 74–76; Fig. 3). Standard digital cameras were placed in a waterproof housing, and the cameras were set to take a picture at noon every day using an attached electronic timer (Fig. 3). All systems were in operation by 6 May. With this monitoring system, it was hoped that it would be possible to correlate exactly the date of ice-out (derived from photographs) with changing water temperature and local meteorological data.

A return visit to the study sites was made in August and AWS data and the camera images were downloaded in the field (Fig. 2). At the same time the thermistor chains were changed, and then returned to the lakes. Although the intention of the project was to record data over two ice-melt periods, this late summer visit meant that if the lake-water temperature thermistor chains were lost during the winter of 2000–2001, data for the first ice-melt period was secure. Unfortunately, it was found that one camera had failed to record any images and another took only random images.

The photographic sequence at Lakes 75 and 76 showed that the final break-up of the ice is very rapid. The water temperature record derived from the thermistors indicates that there is a rapid increase in temperature (*c.* 5°C over a few hours) associated with the final break-up of the ice (Fig. 4B). This temperature rise is, presumably, due to the mixing of the water column and transfer of 'warmer' water (*c.* 4–5°C) from depth. Over the ~ 10 days prior to the final break-up of the ice there is a gradual warming of the surface water under the ice due to either radiative heating as the ice thins (and day length increases) and/or the transfer of warmer water from the littoral moats. Using the rapid rise in temperature as an indication of ice break-up we were able to estimate the dates of ice-out at the other lakes. The earliest lake to be ice-free in 2000 was Brayasø (Lake 4) on 6 June. This lake was followed closely by Lake 85 (which drains into Brayasø) on 7 June and Lake 76 on 9 June. Lake 75, although immediately adjacent to Lake 76 is much larger (144 ha versus 8.6 ha)

Fig. 4. **A**: Overlooking Lakes 75 (still ice-covered) and 76 showing the effect of lake area and depth on ice break-up. Camera on hill top (**arrow**) and camp site (**arrow**) between lakes with an inter-distance of 1.56 km (15 June 2000). For location, see Fig. 1B. **B**: Plots of surface-water temperature for all lakes showing the very clear rise in temperature associated with the final break-up of the ice and mixing of the water column. Lake 4 = Brayasø.



and as a result ice-out was delayed by nearly 10 days (18 June 2000; Fig. 4A). Finally, as with our previous field experience, the coastal site (Lake 78) was the last to be ice-free on 25 June 2000. We were not able to retrieve the thermistor string from Lake 21 during our late August field trip and so the ice-out date there is unknown. The lake lies close to the Inland Ice margin and it remains to be seen whether there is a pronounced effect associated with the strong meteorological gradient in this area (Hasholt & Søgaard 1976).

One of us (K.P.B.; see Brodersen *et al.* 2001, this volume) was present in the field at the time of the break-up of the ice on Lake 76 and field observations confirm the rapidity and timing of the ice break-up at this lake (Fig. 4A). Although only one lake, these field observations lend support to the reliability of the camera results. The use of remote-controlled cameras offers a relatively cheap means of tracking environmental change visually on a seasonal basis.

Conclusion

Understanding ice phenology in West Greenland is vital to our understanding of long-term lake-climate interactions and interpretation of the sediment record. Sediment coring at lakes around Søndre Strømfjord indicates considerable variability in both lake biota and physical properties. Some of the long-term trends will be related to soil and landscape development as well as climatic change during the Holocene. However, much of the finer, short-term variability is presumably related to factors such as length of ice cover and processes controlling transfer of nutrients from catchment to lake. Finally, modelling of earlier climate-lake interactions using lake energy balance models requires a fuller understanding of present-day relationships between ice cover period, water temperature and regional meteorological conditions. The different automatic monitoring equipment used in the present study (digital cameras, temperature thermistors and AWS) represents a reasonably cost effective way of acquiring important site-specific field data on the process of ice-melt in remote lakes.

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Holocene temperature and environmental reconstruction from lake sediments in the Søndre Strømfjord region, southern West Greenland

Klaus P. Brodersen, Claus Lindegaard and N. John Anderson

Instrumental temperature records indicate that the mean annual surface-air temperature of the Earth has risen approximately 0.6°C since 1860 (IPCC 2001). Increased global warming can have considerable influence at high latitudes, and among the major concerns are the effects on the sensitive arctic ecosystems and the possible reduction in the diversity of regional flora and fauna. Arctic organisms are highly adapted to extreme environmental conditions and have difficulties coping with any additional stresses or disturbances.

In the ongoing palaeolimnological projects in West Greenland (Anderson & Bennike 1997; Brodersen & Anderson 2000) we address to what extent climate variation has influenced the low-arctic West Greenland lakes during the Holocene. Palaeolimnological data provide independent information on the recent warming, and also place the 19th to 20th century (instrumental temperature records) warming in a long-term context. The sedimentary records allow us to look at the lake-specific ecological response to regional temperature fluctuations over the last several centuries to millennia. This perspective is an important capability in any aim to predict the possible outcome of late 20th century global warming. An important prerequisite, however, is to have good knowledge of the present lake-ecological conditions and the regional climate variability in southern West Greenland, keeping in mind that West Greenland regionally has experienced a decline in average temperature in the second half of the 20th century (Heide-Jørgensen & Johnsen 1998; see also Mikkelsen *et al.* 2001, this volume).

Recent limnology and palaeolimnology

Most groups of plants and animals respond more or less directly to the ambient temperature and climate conditions. The non-biting midges (Diptera: Chironomidae)

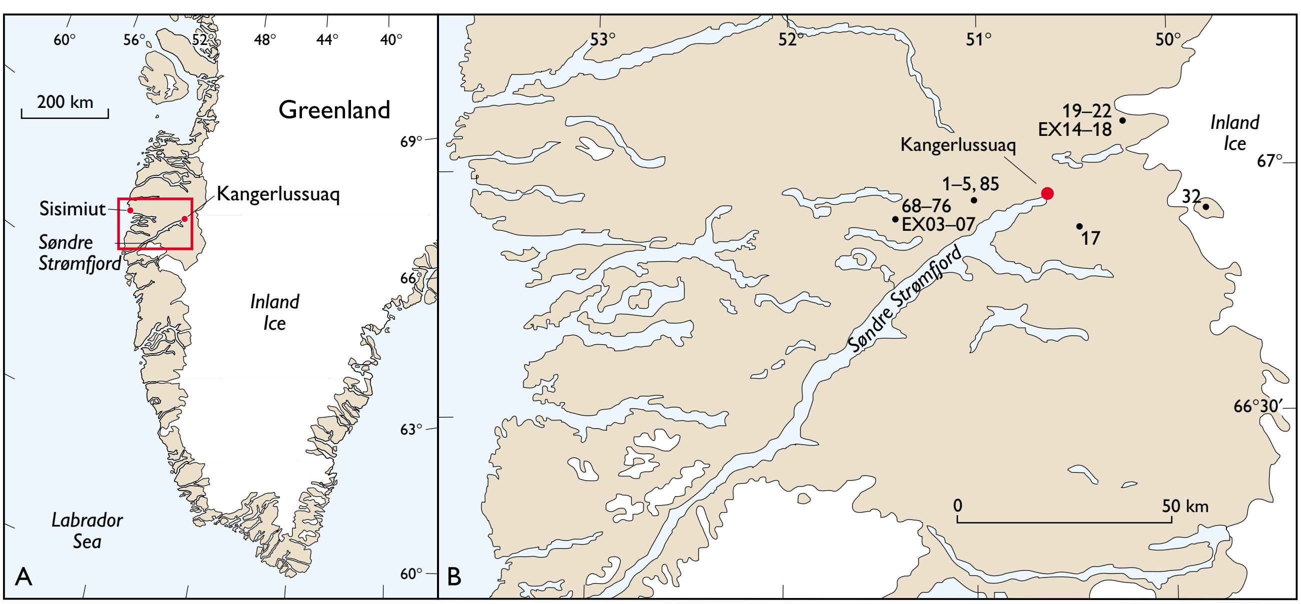

Fig. 1. **A**: Map of southern Greenland showing the location of the study area. **B**: Map of the area at the head of Søndre Strømfjord showing the location of lakes and ponds mentioned in the text and in Table 1. Modified from Anderson *et al.* (2000).

Table 1. Lakes and ponds sampled for chironomid exuviae from 14–24 June 2000

Lake code	N lat.	W long.	Lake type	Conductivity (µS cm-1)	Total nitrogen (mg l-1)	Altitude (m)
SS05	66°59.400′	51°05.300′	B	4072	0.77	175
SS03	66°59.900′	51°01.700′	B	3601	0.80	175
SS17	66°59.400′	50°35.900′	B	2798	1.26	215
SS04	66°59.300′	51°02.800′	B	2636	0.96	170
SS71	66°57.600′	51°31.950′	B	1465	1.86	240
SS85	66°58.900′	51°03.400′	B	616	1.12	178
SS75	66°56.390′	51°33.330′	B	226	0.05	340
SS70	66°57.260′	51°34.950′	D	2443	0.40	235
SS68	66°56.730′	51°35.070′	D	376	0.35	240
SS76	66°56.300′	51°33.300′	D	346	0.36	345
SS72	66°57.802′	51°31.860′	D	311	0.37	255
SS73	66°57.920′	51°29.810′	D	268	0.13	270
SS74	66°56.360′	51°34.510′	D	234	0.00	330
SS02	66°59.800′	50°58.200′	C	321	0.65	185
SS69	66°56.950′	51°35.930′	C	211	0.63	230
SS21	67°09.500′	50°20.400′	C	148	0.37	470
SS01	66°59.200′	50°55.700′	C	128	0.75	120
SS22	67°10.000′	50°19.900′	C	113	0.26	470
SS20	67°09.100′	50°19.500′	C	107	0.41	445
SS19	67°08.500′	50°18.300′	C	85	0.45	470
EX14	67°10.004′	50°19.735′	C	*	*	450
EX04	66°56.539′	51°33.938′	A	423	*	318
EX03	66°56.605′	51°33.800′	A	398	*	318
EX05	66°57.052′	51°31.676′	A	*	*	381
EX06	66°56.828′	51°33.532′	A	*	*	321
EX07	66°56.631′	51°31.020′	A	*	*	380
EX17	67°10.116′	50°20.432′	A	*	*	479
EX18	67°09.950′	50°20.929′	A	*	*	472

Lakes are arranged according to lake type and decreasing conductivity. Lake types are defined from the ordination of species compositions in Fig. 4. SS-lakes are lakes included in the surface sediment sampling program. EX-ponds are additional ponds only sampled for exuviae in June 2000.
* Water chemistry data are not available for the shallow ponds.

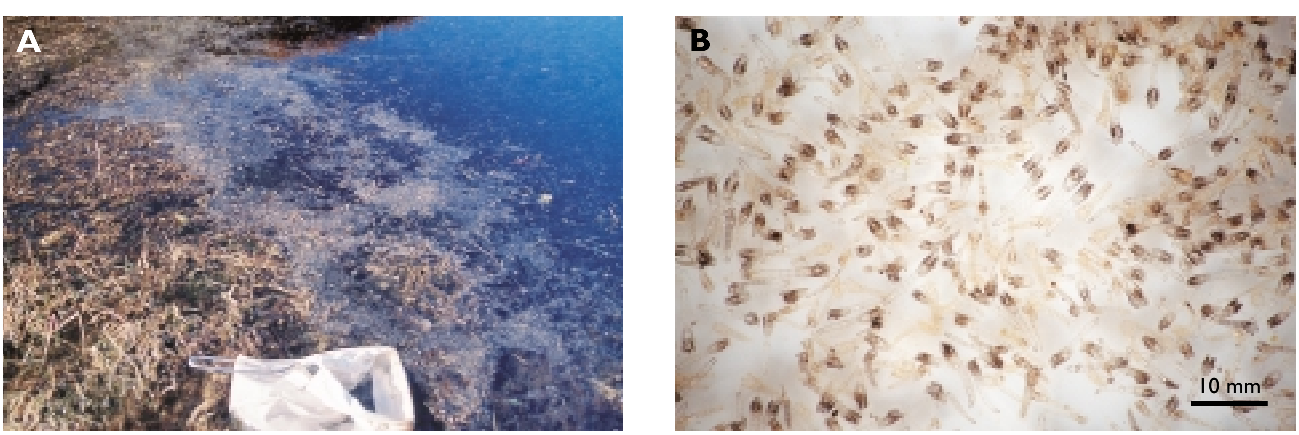

Fig. 2. **A**: Large numbers of floating chironomid exuviae (pale-coloured patches) along the shore of a shallow pond (EX05). For location, see Fig. 1. **B**: Close-up of exuviae, primarily *Chironomus* sp. 3 and *Procladius* sp. 1.

are now accepted as being one of the best biological palaeoclimate proxies (Walker *et al.* 1991; Lotter *et al.* 1999; Olander *et al.* 1999; Battarbee 2000; Brooks & Birks 2000). Subfossil chironomid head capsules are well preserved in lake sediments and by numerical modelling of the relationship between recently deposited subfossil assemblages and the contemporary lake conditions (physics, chemistry and biology) it is possible to quantitatively infer palaeotemperature and to reconstruct past climate variation in the region (Brodersen & Anderson 2000).

Chironomid exuviae

In June 2000, surface sediments were sampled, lake temperature and conductivity profiles were measured and chironomid exuviae collected from 20 of the study lakes initially sampled by Anderson *et al.* (1999) and from eight additional shallow ponds (Fig. 1; Table 1). Exuviae are the cast skins left from the pupae when the aquatic larvae metamorphose into the terrestrial winged adult stage. The exuviae are collected from the lake shores and can sometimes be found in very large numbers when a synchronised mass swarming has occurred, often during or immediately after ice-melt (Fig. 2). The chironomid exuviae can be identified to genera (Wiederholm 1986) and many Palaearctic taxa can be identified to species level (Langton 1991). The knowledge gained from identification of recent exuviae improves our ability to correctly identify the subfossil larval remains from the lake sediments (Fig. 3).

Twenty-two chironomid taxa were registered (Table 2), and several appear to be intermediate types between Palaearctic and Nearctic species. Collected and described material from Greenland is still scarce and the application of West Palaearctic identification literature is problematical.

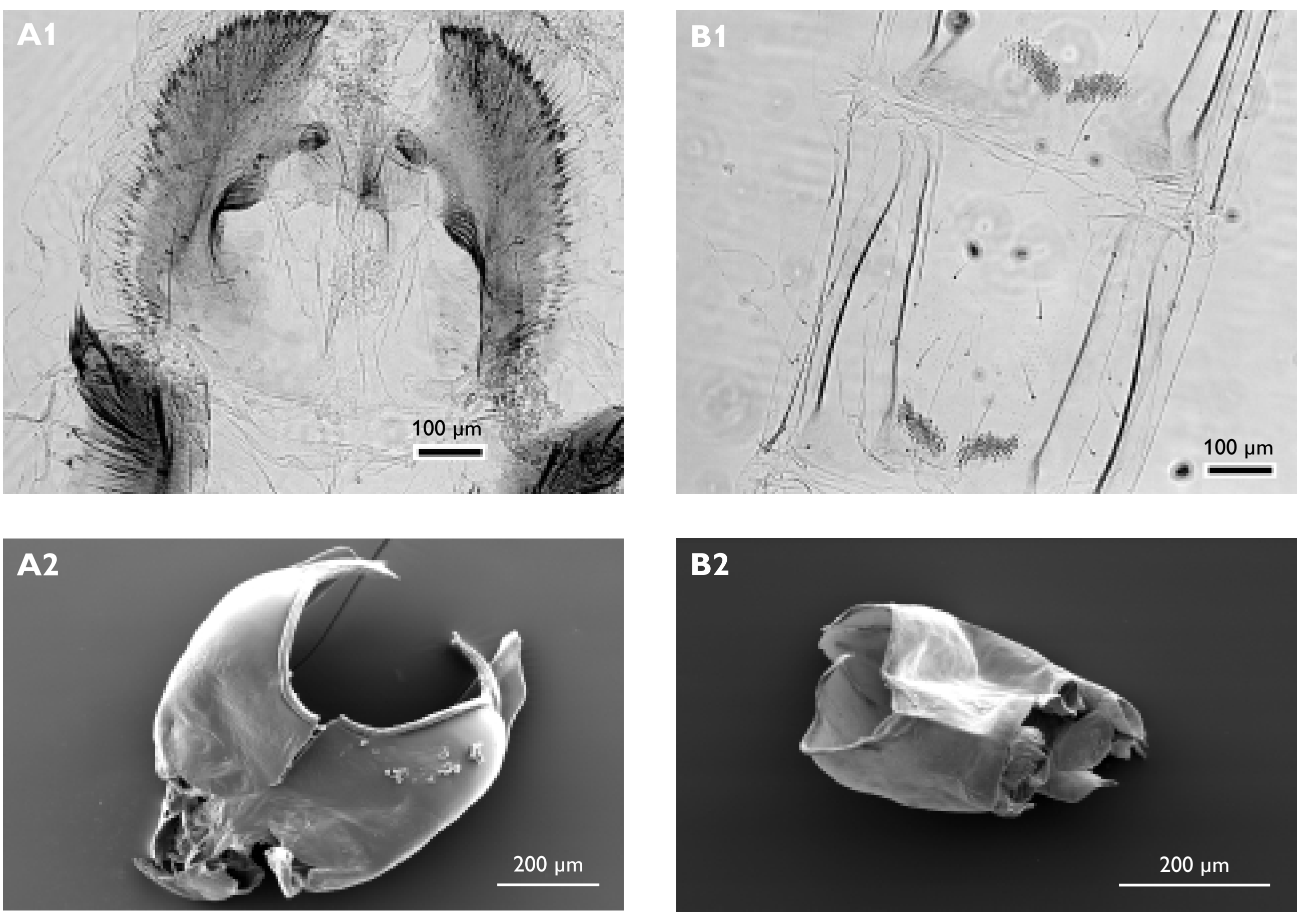

Fig. 3. **A1**: Posterior abdominal segment of *Chironomus* sp. 1 pupae (from pond EX18); **A2**: Larval head capsule of subfossil *Chironomus* sp. (from Lake SS32). **B1**: Abdominal segments of *Micropsecta brundini* (from Lake SS19); **B2**: Larval head capsule of subfossil *Micropsectra* sp. (from Lake SS32). A1 and B1 are light micrographs; A2 and B2 are scanning electron micrographs. For lake locations, see Fig. 1 and Table 1.

Table 2. Chironomid exuviae collected in West Greenland lakes and ponds from 14–24 June 2000

Taxon	Number of lakes	Lake type
Ablabesmyia pulchripennis (Lundbeck 1898)	4	B
Arctopelopia melanosoma (Goetghebuer 1933)	1	B
Procladius sp. 1	7	A
Procladius sp. 2	7	B
Chaetocladius sp.	1	D
Corynoneura arctica Kieffer 1923	12	BC
Heterotrissocladius sp.	7	CD
Psectrocladius barbimanus (Edwards 1929)	14	ABC
Psectrocladius limbatellus (Holmgren 1869)	3	DC
Psectrocladius octomaculatus Wülker 1956	1	C
Orthocladius olivaceus Kieffer 1911	1	C
Chironomus sp. 1	8	AB
Chironomus sp. 2	6	AB
Chironomus sp. 3	3	AB
Dicrotendipes modestus (Say 1823)	8	AB
Micropsectra brundini Säwedal 1979	13	CD
Micropsectra groenlandica Andersen 1937	1	C
Micropsectra lindrothi Goetghebuer 1931	1	D
Paratanytarsus laccophilus (Edwards 1929)	1	A
Tanytarsus gracilentus (Holmgren 1883)	7	BC
Tanytarsus norvegicus (Kieffer 1924)	1	C
Tanytarsus sp. 2	1	C

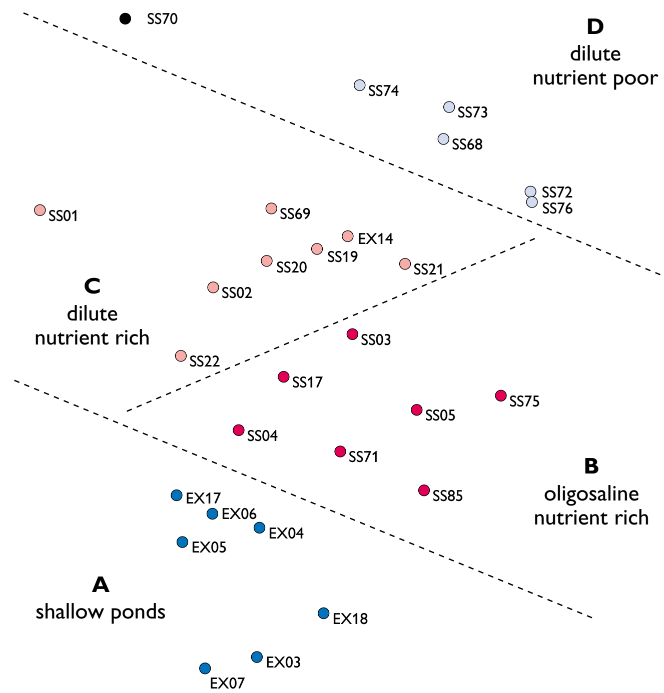

Fig. 4. Non-metric multidimensional scaling (NMDS) of 28 chironomid exuviae samples from southern West Greenland. Lakes in the ordination diagram are plotted along arbitrary axes according to their similarity in species composition. High proximity reflects high species similarity. Lakes (**dots**) are coloured according to lake groups. For lake locations, see Fig. 1 and Table 1.

Non-metric multidimensional scaling (NMDS; Clarke & Warwick 1994) based on similarities in species composition in the 28 lakes and ponds clearly demonstrates the value of chironomids as environmental indicators (Fig. 4). Lakes (and ponds) that group close together in the ordination diagram have high similarity in chironomid assemblages and the preference lake types for the 22 taxa are given in Table 2. The ponds (group A) and the 'oligosaline nutrient-rich' lakes (group B) were characterised by warm-water species that inhabit shallow lakes or the littoral zone of deep lakes (*Chironomus* sp., *Ablabesmyia pulchripennis*, *Procladius* spp., *Dicrotendipes modestus*). The meromictic oligosaline lakes (group B) are almost permanently stratified (Brodersen & Anderson 2000) and species that characterise the deep profundal zone are absent in these lakes due to low oxygen levels (Anderson *et al.* 1999). The dilute lakes (groups C and D) are relatively nutrient-poor and less productive and characteristic species are *Heterotrissocladius* sp. and *Micropsectra* spp. The oligotrophic Lake SS75 was misclassified because a few exuviae of *Chironomus* sp. 3 were found in the sample. Two different non-named species of *Procladius* appear to show significantly different lake type preference, suggesting that subfossil *Procladius* head capsules should be carefully identified and separated in palaeolimnological analysis, which is still not possible. In contrast, three species of *Chironomus* did not differentiate significantly in this preliminary numerical analysis.

Subfossil chironomids

Lake surface sediments were collected from a range of lakes and the training set with subfossil chironomid data now constitutes 48 lakes and 28 taxa. High-resolution water temperature data are available for 21 of the lakes and there is a good correlation between the chironomid assemblages and the mean July surface-water temperature ($r = 0.80$, Fig. 5). However, even though temperature is the strongest variable to describe the chironomid distribution, both lake total-nitrogen concentration (TN) and maximum lake depth are also strong environmental parameters ($r = 0.69$ and $r = 0.66$, respectively; authors' unpublished data).

Holocene climate reconstruction

A dated Holocene sediment core from a lake near the harbour at Kangerlussuaq has been analysed and clear stratigraphic signals are recorded (unpublished data). Quantitative temperature reconstructions using the preliminary 21-lake model reveal the same patterns in Holocene cold/warm fluctuations as interpreted through ice cores from the Greenland Inland Ice. The rapid cold event at 8200 ice core years B.P. (Alley *et al.* 1997; Willemse & Törnqvist 1999) is clearly reflected in the sediment core by extreme low chironomid diversity and by dominance of the cold-water indicator *Micropsectra* (Fig. 3). The warmer periods around 2500 B.P. and 3500 B.P. are characterised by warm-water genera such as *Chironomus* (Fig. 3). The sediment cores from West Greenland have been studied by a multiproxy approach that includes diatom-inferred conductivity, plant pigments, zooplankton, stable isotopes and macrofossils (Anderson *et al.* 2000) and the preliminary results show good agreement between the different proxies. This approach allows assessment of lake ontogeny along environmental gradients other than temperature. By addressing the same question simultaneously with different proxies it is possible to identify artifacts of each of them, and the aim of reaching a reasonable *ecological* reconstruction is more conceivable. A common problem in palaeolimnological temperature reconstruction is to partial out the effect of inter-relation between lake temperature and lake productivity. The low productive, oligotrophic lakes are usually also cold, high altitude and deep lakes with small catchment areas, whereas the warm lakes are nutrient-rich and productive lowland lakes often with high organic sediment content (cf. Lotter *et al.* 1997; Müller *et al.* 1998; Olander *et al.* 1999). In the West Greenland data set, strong secondary environmental gradients are also found (TN and lake depth) and one of the aims of this project is to highlight and include these variables in the inference models rather than to discard them.

Long-term lake monitoring and assessment

Compared to the ongoing intensive lake monitoring programs in European countries (Kristensen & Hansen 1994), collection of limnological and environmental data from the sensitive and pristine low-arctic West Greenland lakes must be considered as limited. However, biological remains (i.e. chironomid head capsules and exuviae) from the lake sediments and surface waters integrate information on lake conditions over years and decades and can therefore be used as a long-term monitoring tool in these remote areas where frequent data registration is difficult and where existing environmental records do not exist (Smol 1992). The data collected during this project can thus provide a standard of reference in future evaluation of changes in lake conditions and typology on decadal time scales (Brodersen *et al.* 1998). The studies of collected exuviae samples from West Greenland, presented here for the first time, are also valuable for verification of identified subfossil material.

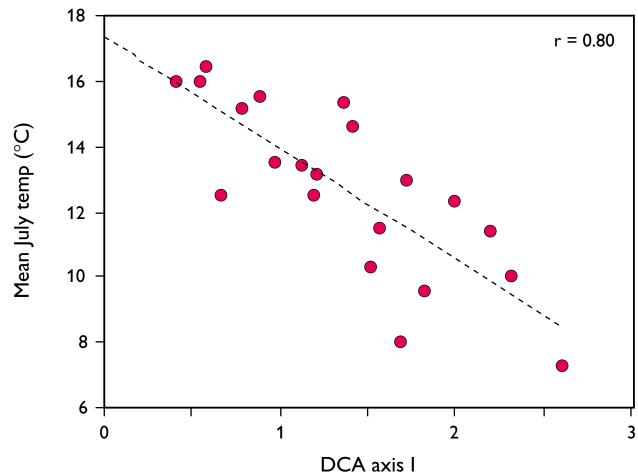

Fig. 5. Correlation between subfossil chironomid assemblages and the mean July surface-water temperature (°C) from 21 lakes. Chironomid assemblages are expressed as the axis one scores of a detrended correspondence analysis (DCA; Hill & Gauch 1980).

Future work

In future field seasons we intend to expand the calibration data set in the low end of the temperature gradient by including glacier-near lakes (late-glacial analogues) and also lakes at higher altitudes, although the latter might introduce new ecological assumptions that need to be taken into account. The ecological responses gained from the lake sediments in southern West Greenland can be compared to ice core data from the Greenland Inland Ice more readily than results from lakes elsewhere. Analyses of Holocene sediment cores from closely located lakes, but with different typology (e.g. salinity and productivity; Fig. 4), will give an idea of similarities in inter-lake overall climate impact as compared to the differences in in-lake dynamic processes. The long time-series provided by the palaeolimnological data therefore not only give an independent idea of past environmental and climate conditions, but also help to assess the natural variability of the biotic and abiotic systems.

Acknowledgements

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Marine and terrestrial investigations in the Norse Eastern Settlement, South Greenland

Naja Mikkelsen, Antoon Kuijpers, Susanne Lassen and Jesper Vedel

During the Middle Ages the Norse settlements in Greenland were the most northerly outpost of European Christianity and civilisation in the Northern Hemisphere. The climate was relatively stable and mild around A.D. 985 when Eric the Red founded the Eastern Settlement in the fjords of South Greenland. The Norse lived in Greenland for almost 500 years, but disappeared in the 14th century. Letters in Iceland report on a Norse marriage in A.D. 1408 in Hvalsey church of the Eastern Settlement, but after this account all written sources remain silent. Although there have been numerous studies and much speculation, the fate of the Norse settlements in Greenland remains an essentially unsolved question.

Previous and ongoing investigations

The main objective of the field work in the summer of 2000 was to continue the marine geological and hydrographic survey undertaken in 1998 and 1999 in the fjord complex of the Eastern Settlement (Kuijpers *et al.* 1999). In addition, the studies aimed to provide input to a collaborative archaeological project with the National Museum of Denmark, investigating environmental changes affecting the descendants of the Norse settlers in Greenland (e.g. Arneborg *et al.* 1999).

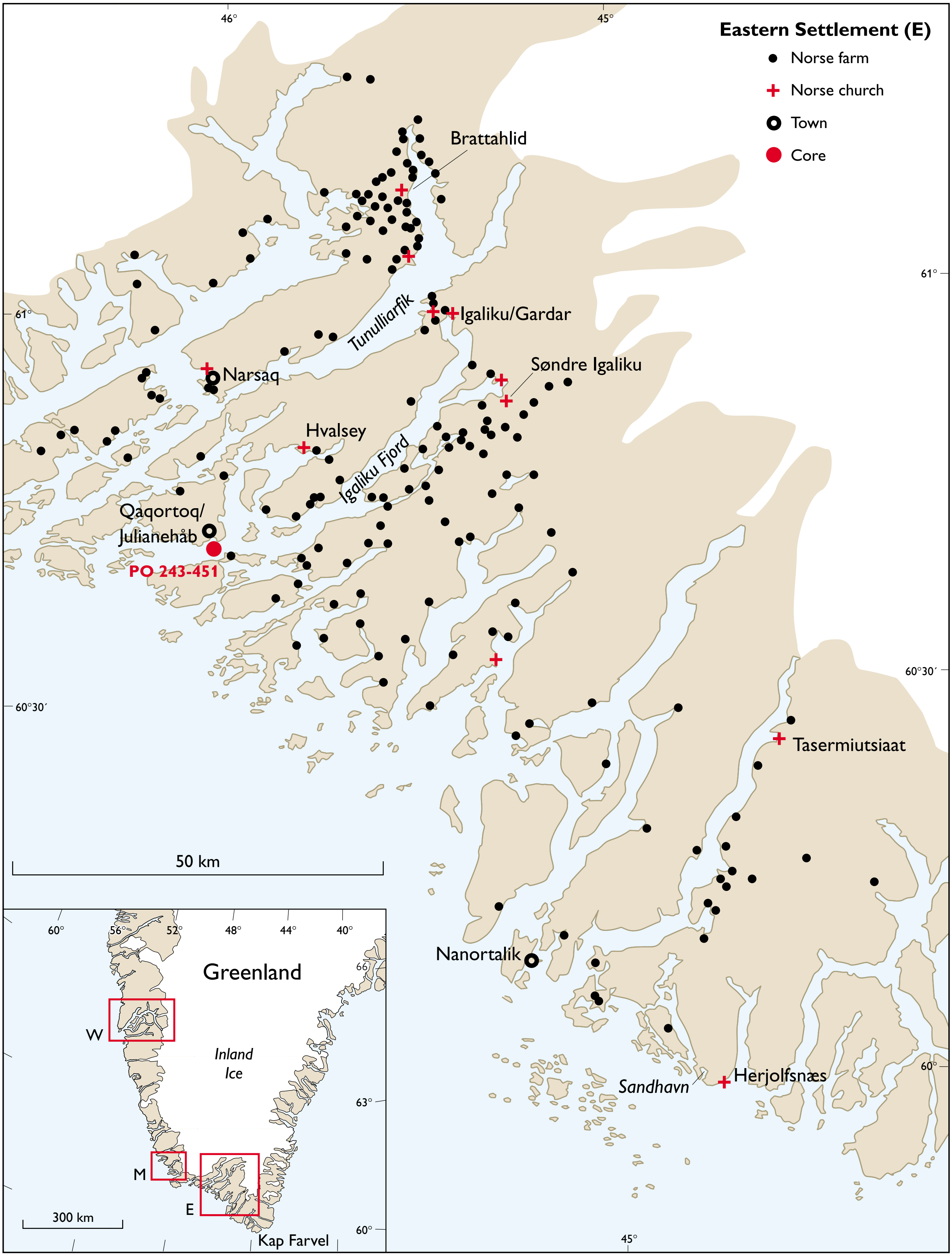
The focus of the investigations was directed towards a detailed survey of Sandhavn, the supposed 'Atlantic Harbour' of the Norse settlers of South Greenland. Sandhavn is close to the major Norse homestead and church of Herjolfsnæs, where archaeological investigations in 1921 provided much insight into the life of the Norse at a late stage of their presence in Greenland (Nørlund 1924). A hydrographic survey of the sheltered bay of Sandhavn was undertaken by the Royal Danish Administration for Navigation and Hydrography, Copenhagen, using the survey vessel *SKA 12* (Fig. 1), and included detailed depth recordings and side-scan sonar data acquisition. The field investigations also included acoustic investigations of possible targets located in 1998 during shallow-water side-scan sonar investigations off Igaliku, the site of the Norse episcopal church Gardar in Igaliku Fjord (Fig. 2). A brief investigation of soil profiles was conducted in Søndre Igaliku, a once prosperous Norse settlement that is now partly covered by sand dunes.

Field observations and preliminary results

Sandhavn

Sandhavn is a sheltered bay that extends from the coast north-north-west for approximately 1.5 km (Fig. 2). The entrance faces south-east and it is exposed to waves and swells from the storms sweeping in from the Atlantic around Kap Farvel, the south point of Greenland. A narrow entrance shelters the bay itself, and a wide sandy beach, a feature that is rarely seen in Greenland, borders the inner harbour.

Fig. 1. The survey vessel *SKA 12* of the Royal Danish Administration for Navigation and Hydrography in Sandhavn; 'Warehouse Cliff' is in the background.


Eastern Settlement (E)
Norse farm
Norse church
Town
Core
Brattahlid
Igaliku/Gardar
Tunulliarfik
Søndre Igaliku
Narsaq
Hvalsey
Igaliku Fjord
Qaqortoq/
Julianehåb
PO 243-451
50 km
Tasermiutsiaat
Nanortalik
Sandhavn
Herjolfsnæs
46°
45°
61°
60°30′
60°
Greenland
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60°
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66°
63°

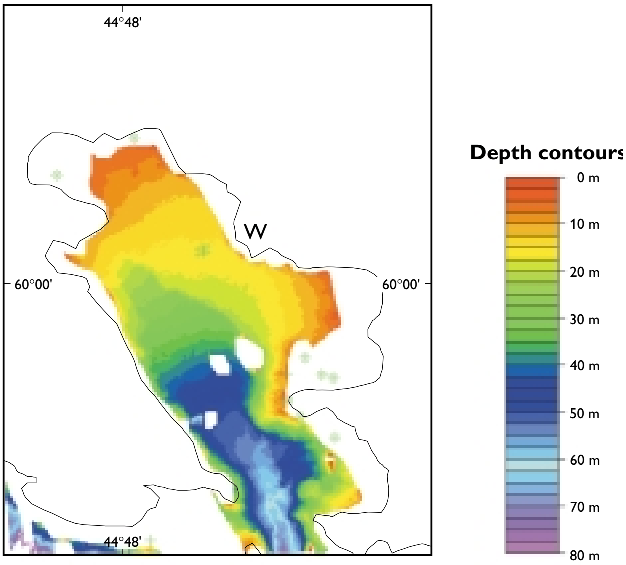

Fig. 3. Depth survey of Sandhavn by the Royal Danish Administration for Navigation and Hydrography showing the narrow entrance to the harbour. The bay offers favourable docking opportunities, in particular at the site here called 'Warehouse Cliff' (**W**).

Fig. 4. Soil profile from the Norse settlement of Søndre Igaliku, showing alternating layers of aeolian sand and darker horizons. Notebook 18 cm long for scale.

The bottom of Sandhavn gently deepens towards the harbour entrance (Fig. 3). It is relatively deep in the vicinity of the 5 m high and steep 'Warehouse Cliff' on which the ruin of a massive Norse stone building is perched. This building is considered most likely to have been a warehouse used by traders, although one might speculate that it had been a chapel serving the seagoing Norse. Taking into account the relative sea-level rise of *c.* 3 m since the Norse lived in the area 1000 years ago (Kuijpers *et al.* 1999), the harbour must have had a different outline and smaller size during the Norse period. Such a bathymetric setting inferred for *c.* A.D. 1000 would favour the location of the 'Warehouse Cliff' as an important docking position for loading and unloading cargo vessels bound to and from Norway and Iceland.

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Fig. 2. Descendants of the Nordic Vikings established the Eastern Settlement in South Greenland around A.D. 1000 during the Medieval Climatic Optimum. The locations of the study areas (Igaliku/Gardar, Søndre Igaliku, Sandhavn/Herjolfsnæs) and core PO 243-451 discussed in the text are indicated. Ruins of Norse farms are marked by **black dots** and the location of churches and monasteries by **red crosses** (modified after Krogh 1982). The index map shows the location of the Norse Eastern Settlement (**E**), the Western Settlement (**W**) and the less important Middle Settlement (**M**).

Søndre Igaliku

Pilot studies were undertaken of soil profiles containing aeolian sand layers close to Norse farms in Søndre Igaliku (Fig. 4). It has been suggested that the extensive sand horizons in the area are the result of soil erosion linked to Norse farming activities (Fredskild 1978; Jakobsen 1991; Sandgren & Fredskild 1991). However, the aeolian deposits are likely to be a result of increased storm activity recorded around A.D. 1300, for which evidence is seen in the marine core PO 243-451 (Lassen *et al.* 2000) taken in nearby Igaliku Fjord (Fig. 2). The profiles show rhythmic alternations of sand and darker horizons, whose age will need to be verified by dating.

The bay off the Søndre Igaliku settlement is today dry at low tide over a large area, but covered by 1–2.5 m of water at high tide. As noted above, previous work in the area (Kuijpers *et al.* 1999) has demonstrated a rise in the relative sea level of at least 3 m during the last 1000 years. It can therefore not be excluded that this vast area was once fertile lowland utilised by the Norse for production of winter hay for cattle. Field investigations in the summer of 2001 will address this problem.

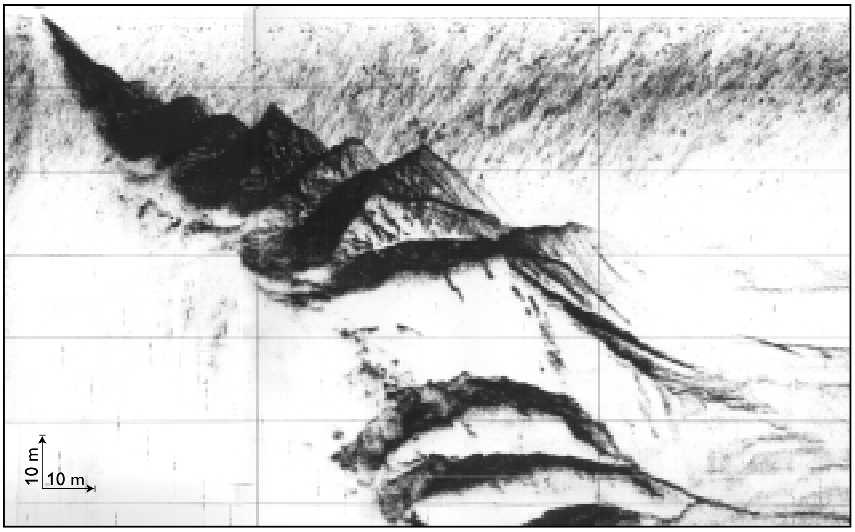

Fig. 5. Sonograph from Igaliku Fjord showing the slope of the delta off Søndre Igaliku with large sand beds concentrated along the northern side of the fjord. Bedforms have a wavelength of 10–15 m, and are up to 3 m high, and were probably generated by sediment deposition from meltwater discharge in a tidal current domain.

A side-scan sonar survey off this tidewater delta showed a spectacular asymmetry in the fjord sedimentation. Whereas high sedimentation rates and large sand waves characterised the relatively shallow seabed along the northern fjord bank (Fig. 5), outcropping bedrock and a much greater water depth indicate mainly non-deposition along the southern fjord bank. This marked difference clearly reflects an estuarine circulation pattern, with a marked Coriolis-force induced asymmetry of sediment-loaded meltwater outflow concentrated along the northern side of the fjord.

Discussion and conclusion

It has been debated whether Sandhavn is the Norse 'Atlantic Harbour' where the Norse landed after an often stormy crossing of the Atlantic. The Norwegian priest Ivar Bardarson (in Jónsson 1930) describes in his sailing directions from *c.* A.D. 1300 that, after crossing the Atlantic, ships would see a tall mountain on a peninsula called Herjolfsnæs, and close by a harbour called 'Sand', regularly used by merchant ships. The area today known as Sandhavn is about 5 km west-north-west of Herjolfsnæs, the site where well-preserved medieval clothing was discovered in the permafrost of the church yard (Nørlund 1924). In the bay area of Sandhavn numerous Norse ruins have been located (Berglund 1988). It is anticipated that the new bathymetric investigations, together with further work planned by the National Museum of Denmark in the summer of 2001, will increase the plausibility of the Sandhavn area being identified as the Norse harbour 'Sand'.

It has been argued that Norse farmers had a major impact on the fragile arctic environment through cultivation of areas around the fjords, and that associated substantial soil erosion was the ultimate cause of the decline and extinction of the Norse culture (Fredskild 1978; Jakobsen 1991; Sandgren & Fredskild 1991). Today intensive sheep farming and cultivation of hay is taking place in some of the same areas that were used by the Norse, and concern has therefore been expressed as to whether these activities might have an adverse environmental impact – comparable to the postulated impact of the former Norse activities. However, preliminary studies of the marine cores and onshore soil profiles indicate that the soil erosion was not a consequence of Norse farming. A more likely scenario is that there is a link between soil erosion and a pronounced increase in the wind stress over South Greenland and the Igaliku Fjord region at the transition from the Medieval Climatic Optimum to the Little Ice Age (Lassen *et al.* 2000). Concern as to the impact of modern farming on the environment is therefore less serious than some have feared.

Field investigations in collaboration with the National Museum of Denmark will continue in 2001 with detailed geomorphological and soil-profile analyses in the vicinity of Søndre Igaliku, while marine investigations will include studies and coring operations off Søndre Igaliku.

To gain additional data and information on the life and gradual change of the natural environment of the Norse in Greenland, a coring programme is planned in 2002 for the inner parts of the Godthåbsfjord system in the Western Settlement (Fig. 2).

Acknowledgements

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The Nalunaq gold prospect, South Greenland: test mining for feasibility studies

Mogens Lind, Lotte Kludt and Brian Ballou

The Nalunaq narrow-vein gold prospect is situated 40 km north-east of Nanortalik, the southernmost town in Greenland, 6 km inland from the fjord Saqqaa (Fig. 1). The exploration licence is held by Nalunaq I/S, a company jointly owned by Crew Development Corporation, Canada (67%) and NunaMinerals A/S, Greenland (33%).

A pre-feasibility study of March 1999 by an independent mining consulting company commented positively on the Nalunaq prospect (Nalunaq I/S, personal communication 1999). However, assessment of the sample database demonstrated considerable variation in grade estimates depending on the use of drillcores, chip or saw-cut samples as well as the capping levels (reducing the highest assay values to a fixed value). To advance this project to the feasibility level, the pre-feasibility study stressed the need for improved grade verification and demonstration of grade continuity.

In preparation for a feasibility study, a Can$ 9 million underground test mining and bulk sampling programme was executed during the summer 2000 field season. Strathcona Mineral Services Limited (Canada) designed the programme in conjunction with Nalunaq personnel. This report focuses on the field aspects of the programme; processing of field and laboratory data is still in progress (January 2001).

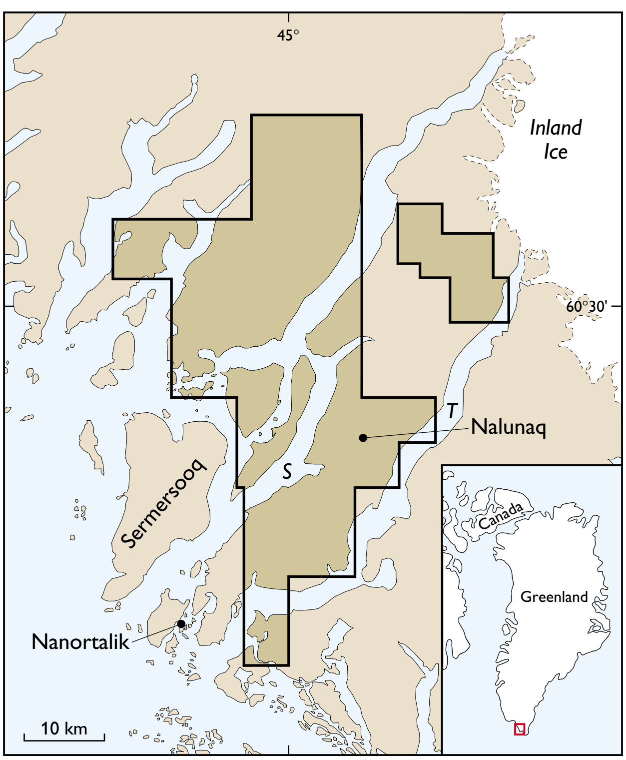

Fig. 1. Map of the Nanortalik region showing the location of the Nalunaq prospect. The framed area is the exploration licence outline. ***S***: Saqqaa; ***T***: Tasermiut.

Geological setting and previous investigations

The Nalunaq gold prospect (see Kaltoft *et al.* 2000 and references therein) is hosted by a Palaeoproterozoic sequence of mafic metavolcanics and dolerite sills metamorphosed under amphibolite facies conditions. The mineralisation is located in a shear zone, and consists of a system of quartz veins associated with calc-silicate alteration referred to as the 'Main Vein' (MV; Fig. 2). Gold occurs mainly in native form with grain size ranging from 1 micron to 4 mm (Fig. 3). The mineralised zone has a strike of *c.* 50° and dips at 25°–55° to the south-east. Two major dextral faults divide the MV into the 'Southern Block', 'Target Block' and 'Upper Block' (Fig. 2). Since 1992 the MV has been mapped and sampled for a distance of *c.* 2000 m on surface outcrops. Diamond drilling, totalling 11 452 m of core from 78 holes, has focused on the 'Target Block' and adjacent parts of the 'Upper Block' and 'Southern Block'. In 1998 a 288 m exploration adit at level 400 m above sea level was excavated in the MV for 205 m along strike within the 'Target Block'. In addition, two upwards-directed shafts (raises) totalling 39 m were excavated in the MV up-dip direction. Significant grade variations on a metre scale were

Geology of Greenland Survey Bulletin 189, 70–75 (2001)

Fig. 2. The east face of Nalunaq mountain. The gold-bearing 'Main Vein' (MV) is traced in **yellow** (not to scale). **Full yellow line** indicates outcropping MV while the **dashed yellow line** indicates continuation of the MV trace below the talus as interpreted from core drilling. Two dextral faults (**dashed white lines**) divide the MV into the 'Southern Block', 'Target Block' and 'Upper Block'. The winding road provides access to the adit portals at levels 350 m, 400 m and 450 m. Mountain summit is *c.* 1100 m above the mining camp on the valley floor. Photo: Hans Christian Langager.

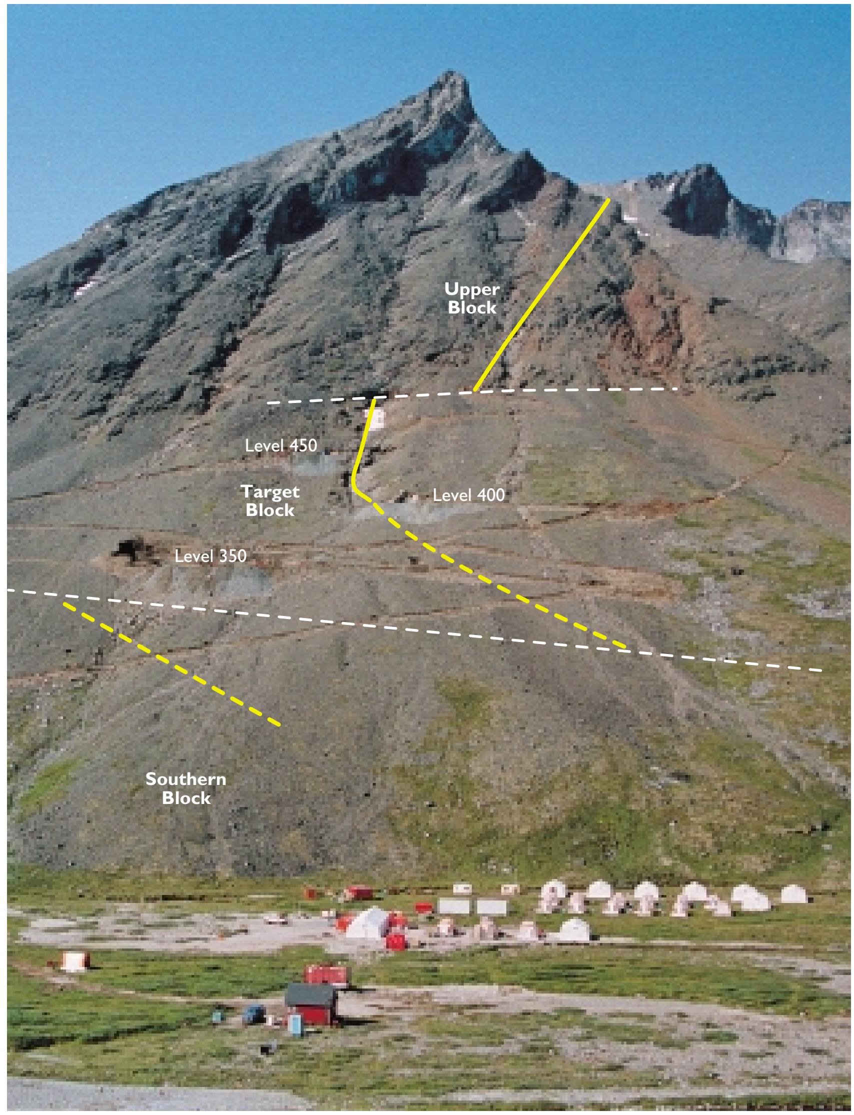

Fig. 3. Visible gold in a sample from the 'Main Vein' surface exposure between the portal at level 450 m and the snowdrift seen on Fig. 2. Grains, such as that on the left side of the photograph, are important contributors to the value of the deposit. Sample GGU 445683. Photo: Jakob Lautrup.

documented by chip and saw-cut channel sampling. Grades as high as 5240 g/t over 0.8 m were recorded from a saw-cut sample. At the current stage of exploration, indicated plus inferred gold resources of 425 000 troy ounces (~ 13.2 tonnes) with an average grade of 32 g/t are estimated. Taking into account a proposed mining method comparable to that used at a similar deposit, and including the losses due to extraction and dilution, the pre-feasibility study estimated a mill-feed grade of 27 g/t.

A geological exploration target of about 1.8 million ounces of gold (~ 56 t) is currently envisaged from the mineralised structure. This figure includes the indicated and inferred gold resources, plus an order-of-magnitude estimate based on geological modelling.

Programme objective

The prime focus of the summer 2000 programme was to investigate a section of the existing mineralised area in order to establish resources that would meet bank-financing requirements. The target amount of resources was based on the capital and operating costs detailed in the pre-feasibility study that would support a 500 tonnes-per-day (tpd) operation. Furthermore, the project needed to establish a strike length of at least 400 m in order to obtain the 500-tpd scenario of the pre-feasibility study.

To test the continuity of mineable gold grade (approximately 25 g/t over the mining width including waste dilution) the MV was exposed through the excavation of adits at three levels and construction of raises in the MV up-dip direction. This was combined with a rigorous scheme for geological mapping and sampling. The adit/raise design was set up to outline 80 × 80 m blocks within the MV plane (Fig. 4). The blocks were exposed and sampled on three or four sides, depending on their position in relation to the underground workings and the surface outcrops. Most blocks also included drill-hole intersections. The adits were advanced to expose the vein for a strike length of 400 m.

Grade verification was approached by extensive bulk sampling. This is a recommended industry practice for gold deposits with a significant nugget effect (John & Thalenhorst 1991). Each bulk sample was processed separately through a crushing/screening/sampling plant situated on the valley floor (see Fig. 6). To address the well-known problem of obtaining representative samples from broken ore, this part of the programme was based on sampling theory as formulated by Gy (1982) and extended by François-Bongarçon (1998). The purpose was to minimise the 'Fundamental Sampling Error' (FSE) occurring at each sample reduction step. To obtain calibration data for designing the sampling programme, Lakefield Research Limited (Canada) conducted bench-scale metallurgical tests on a number of existing MV samples. The overall FSE for an expected 20 000 t of Nalunaq bulk sample material at an average gold grade of 25 g/t was calculated to ± 2.5% (equivalent to ± 0.6 g/t). It should be noted that the 23 000 t actually mined to achieve the programme objective constitutes about 5% of the indicated plus inferred resources.

Underground work

Underground development totalled *c.* 1900 m of adits and raises (Fig. 4). The 1998 adit at the 400 m level was extended to a length of 400 m and two new adits were excavated at the 350 m and 450 m levels to lengths of *c.* 400 m each. In addition 13 raises were driven in the MV plane up-dip to lengths of up to 80 m. For practical reasons each advance of an adit heading (a 'round') was carried out by full-face blasting. The vein was deliberately kept in the middle of the advancing face for systematic geological sampling of both the hanging wall and foot wall structure (Fig. 5). In an actual mining operation the mineralised vein would be carried high up in the working face to allow the use of a mining technique (resuing) whereby the foot wall waste-rock of each 'round' is blasted and removed before blasting of the MV material.

A number of minor faults with dextral displacement were encountered during excavation of the adits. This necessitated offsetting the adits to the right to regain contact with the MV (the kinks on the adit outlines in Fig. 4). Some of the faults could be traced between the levels, and on occasions a raise was stopped prematurely in waste after intersecting the fault plane.

A 10 × 10 m test stope was mined to obtain information which will facilitate the choice of an optimal mining method of the MV between the sublevels. The aim was to test the minimum practical mining width to be achieved at conditions reflecting production mining. It would also allow observations on the rock mechanical properties of the hanging wall in particular, as this will influence the selection of stope dimensions during mine planning.

The excavated material (*c.* 70 t) from each adit 'round' was treated as a separate bulk sample. In contrast, four raise 'rounds' were combined to one bulk sample (a

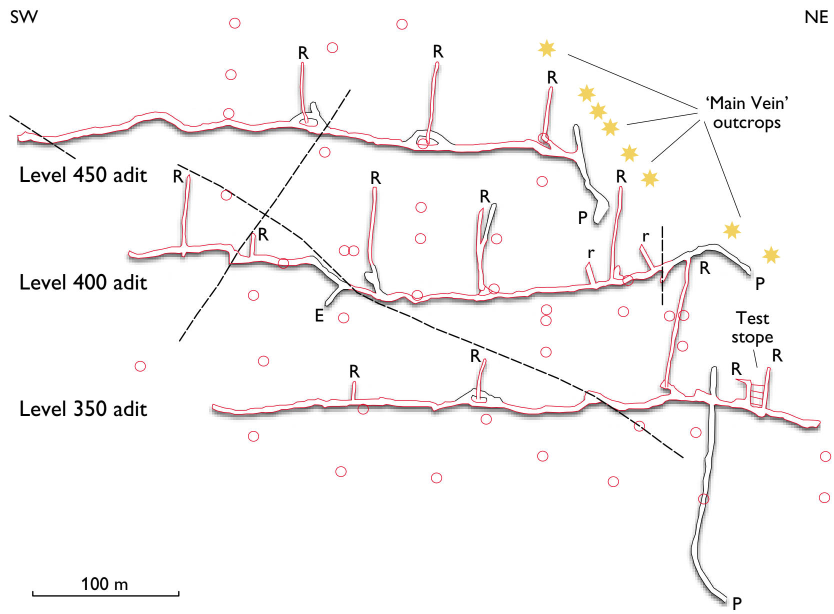

Fig. 4. Longitudinal section drawn in the plane of the 'Main Vein' (MV), which has a strike of 050° and is inclined at 40° to the south-east (average MV dip), showing adits and raises (**r**, 1998; **R**, 2000). **Black lines** indicate development in waste to access the MV; **red lines** indicate development in ore. The **red ribbed pattern** in the test stope illustrates mining of the ore by segments between the two short raises. The **dashed lines** mark the trace of minor dextral faults with metre-scale offsets. **Open red circles** indicate positions of drill-hole intersections with the MV. **Yellow stars** are MV outcrops. **E** is the end of the 1998 adit, and **P** the adit portal (visible on Fig. 2).

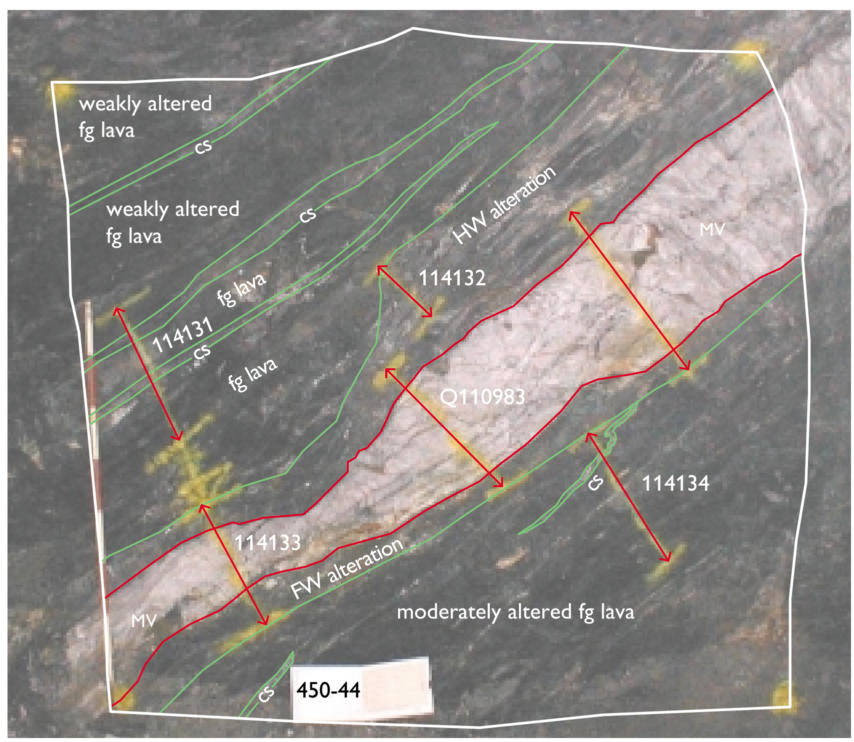

Fig. 5. Face for round 44 at level 450 (face limits shown by **white frame** with **white label** at the bottom of the face). The mapping and sampling routine is described in the text. **Green lines** indicate limits of calc-silicate alteration (**cs**). Other abbreviations – **fg**: fine-grained; **FW**: foot wall; **HW**: hanging wall; **MV**: 'Main Vein'. The **red lines** show the positions of the channel samples – **114131**: HW sample; **114132**: alteration zone; **114133**: MV sample (material from the three channels across the MV is combined to one sample); **114134**: FW sample; **Q110983**: 'quick' sample (chip) for immediate analysis (obtained parallel to the centre MV sample). **Bars** on the ranging rod are 20 cm long.

'raise segment') of about the same weight as one adit 'round'. Much attention was paid to recovery of all broken rock at the adit headings and below the raises. Temporary stockpiling during haulage was on a 'round-by-round' basis on numbered concrete pads. Each time a bulk sample was moved, the pad was thoroughly cleaned, and the recovered fines added to the sample in order not to lose gold grains liberated during blasting and haulage of the broken rock.

Each face was geologically mapped and sampled. The face map for 'round' 44 at the 450 m level is illustrated in Fig. 5. The position and outline of each face was surveyed in relation to the mine grid. 'Main Vein', alteration halo, shearing and other features were traced in

Fig. 6. Crushing and sampling plant at the valley floor below the 'Nalunaq' mountain (*c.* 500 m south of the camp in Fig. 2). See text for description of sample flow. Note the front-end-loader beside the sample tower and the person near centre of photograph for scale. Photo: Hans Christian Langager.

detail and the presence of visible gold noted. The layout for the saw-cut channel samples (2–4 kg) is shown on Fig. 5. Three samples were taken across the MV extending a few cm into the wall-rock to include gold located at the MV/wall-rock contact. The material from the three MV samples was combined to one sample. Depending on the width of the alteration zone, this phase was sometimes sampled independently in continuation of one of the MV samples. Samples were also obtained from the hanging wall (HW) and the foot wall (FW). A supplementary chip sample was taken parallel to the centre MV sample for immediate analysis. Raises were chip-sampled only, due to practical considerations. All map and sample information was digitised and saved together with a digital photograph of the face as individual layers in MapInfo (Geographical Information System). The area of the map units (MV, alteration zone, HW and FW) was determined for each face as part of the digital processing.

All the face samples were analysed by XRAL Laboratories (Canada) by the Screen Fire Assay method. When assay data become available, the corresponding sample grade will be assigned to each of the geological map units together with a specific gravity from the calibration tests on Nalunaq reference samples by Lakefield Research Limited. The grade of each face will then be estimated by weighting grades by area and specific gravity. The estimated grade of a 'round' is the average of the two enclosing faces and will be compared to the grade of the corresponding bulk sample.

Bulk sample processing

The crushing and sampling plant is shown in Fig. 6. A total of 388 bulk samples were processed. A front-end loader feeds coarse blasted rock from one of the pads to a two-stage crushing circuit for reduction to less than 20 mm ('fine ore'). This material is hauled to one of the 'fine ore' bins.

'Fine ore' is fed to the top of the sample tower (Fig. 6) by a conveyor belt. On its way down the tower the 'fine ore' is passed through three consecutive sample splitters. A roll crusher is positioned between the second and third splitter for further reduction of the sampled 'fine ore' to less than 6 mm. The sample material from the third splitter is manually fed through a riffle splitter, until the field sample of *c.* 35 kg is obtained. This is equivalent to 0.05% of the 70 t tower feed from a typical adit 'round' or 'raise segment'.

The rejects from the two first splitters are discharged to a pile beside the tower. Rejects from the two last splitters are collected in a numbered tote bag. After weighing (0.8–1 t) the tote bag is stored as reference material.

The tower rejects were hauled to either the 'high grade' or 'low grade' rejects pile (Fig. 6). This distinction is based on the geological face mapping, where observations of visible gold in the corresponding face automatically classify a bulk sample as 'high grade'.

The field samples were shipped to Lakefield Research Limited for laboratory treatment. At the laboratory, gold was determined by the Screen Fire Assay method following several stages of screening/crushing/splitting.

Implications for mining

With respect to adding tonnage to the resource, the 400 m and 450 m levels are encouraging, as they were both advanced beyond the innermost drill section, and thus tested new ground (Fig. 4). Grade data are not yet available, but repeated observations of visible gold are a positive indicator.

The bulk sampling results from the adits and raises cannot be taken as a direct prediction of a production mill-feed grade, because the full-face advance would include a substantial amount of waste, compared to the resuing method to be applied during production mining. However, the grade of the bulk sample can be calculated over the width of the MV due to the detailed measurements of face size and MV size during the development. The bulk sampling results will provide a reliable estimate of the amount of gold contained in the excavated material. As this information is available on a 'round-by-round' basis, these numbers can be used both to test the continuity of gold mineralisation and to outline patterns in gold distribution in strike and dip directions. These figures can be compared to the calculated grades from the face samples, to ascertain how channel/chip sampling can be used to predict grades. This will also allow selection of capping levels based on the specific conditions of the deposit, rather than using standard statistical techniques.

The geological mapping programme provides information for detailed mine planning. The pre-feasibility study suggested mining by development of sublevels using the resuing technique. Extraction of the blocks between the sublevels would then be undertaken by long-hole stoping. A detailed control on fault geometry will be essential for stope layout. The acute angle of intersection observed between some of the faults and the MV (Fig. 4) indicates that a fault may influence a substantial part of a stope block, and this will have to be taken into account during stope design. The work in 2000 also demonstrated that much of the waste development required to access the vein for mining in the 'Target Block', as proposed in the pre-feasibility study, will not be required as the mineralised material can be brought to the surface and taken down to the process plant. Furthermore, observations from the raises showed the vein to be much straighter than anticipated between the levels, which should allow for longer dimensions between the sublevels thereby reducing the required access development.

If a mine is established, then the existing adits can be incorporated as sublevels in the mine. Furthermore, the 23 000 t of tower rejects will constitute a measured resource.

Acknowledgements

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Reconnaissance for noble metals in Precambrian and Palaeogene rocks, Amdrup Fjord, southern East Greenland

Bjørn Thomassen and Johan Ditlev Krebs

A zone of hydrothermal veins in the Kangerlussuaq region, southern East Greenland, is the focus of a one-year project by the Geological Survey of Denmark and Greenland (GEUS). The project aims to localise, map, sample and analyse silver-gold-bearing veins in a selected area of Precambrian and Palaeogene rocks north of Amdrup Fjord (Figs 1, 2). This report describes the field work and presents some preliminary results.

The study area comprises a *c.* 3 km wide and 10 km long ridge between Amdrup Fjord and Søndre Syenitgletscher, centred on the 938 m high mountain Flammefjeld (Figs 2, 3). The area is of alpine character with small glaciers and with extensive snow cover most of the year. The field programme was chosen to coincide with the time of minimum snow cover, from 25 July – 23 August. During this period, the major part of the area was investigated on daily foot traverses from four fly camps, helped by helicopter lifts on two occasions. Logistically, the work was part of a larger expedition to East Greenland – *EG 2000* – organised by the Danish Lithosphere Centre and GEUS, which is reported on elsewhere (Nielsen *et al.* 2001, this volume). A temporary field base in Sødalen, some 50 km east of Amdrup Fjord, supported the expedition's Ecureuil AS 350 helicopter and provided services for the field teams of the various activities attached to *EG 2000*. Air connections with Iceland were maintained by Twin Otter aircraft operating from a gravel landing strip in Sødalen (Fig. 1).

Geological setting

The Kangerlussuaq region of southern East Greenland is underlain by a Precambrian crystalline basement

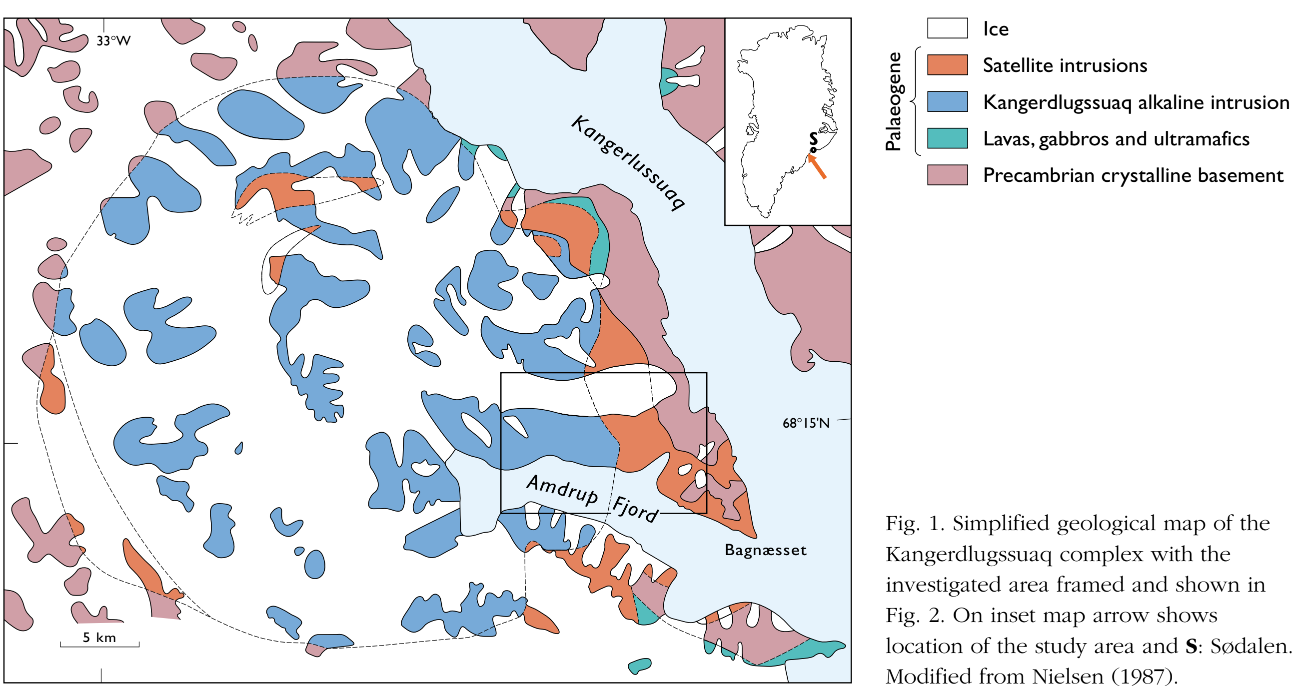

Fig. 1. Simplified geological map of the Kangerdlugssuaq complex with the investigated area framed and shown in Fig. 2. On inset map arrow shows location of the study area and **S**: Sødalen. Modified from Nielsen (1987).

Geology of Greenland Survey Bulletin 189, 76–82 (2001)

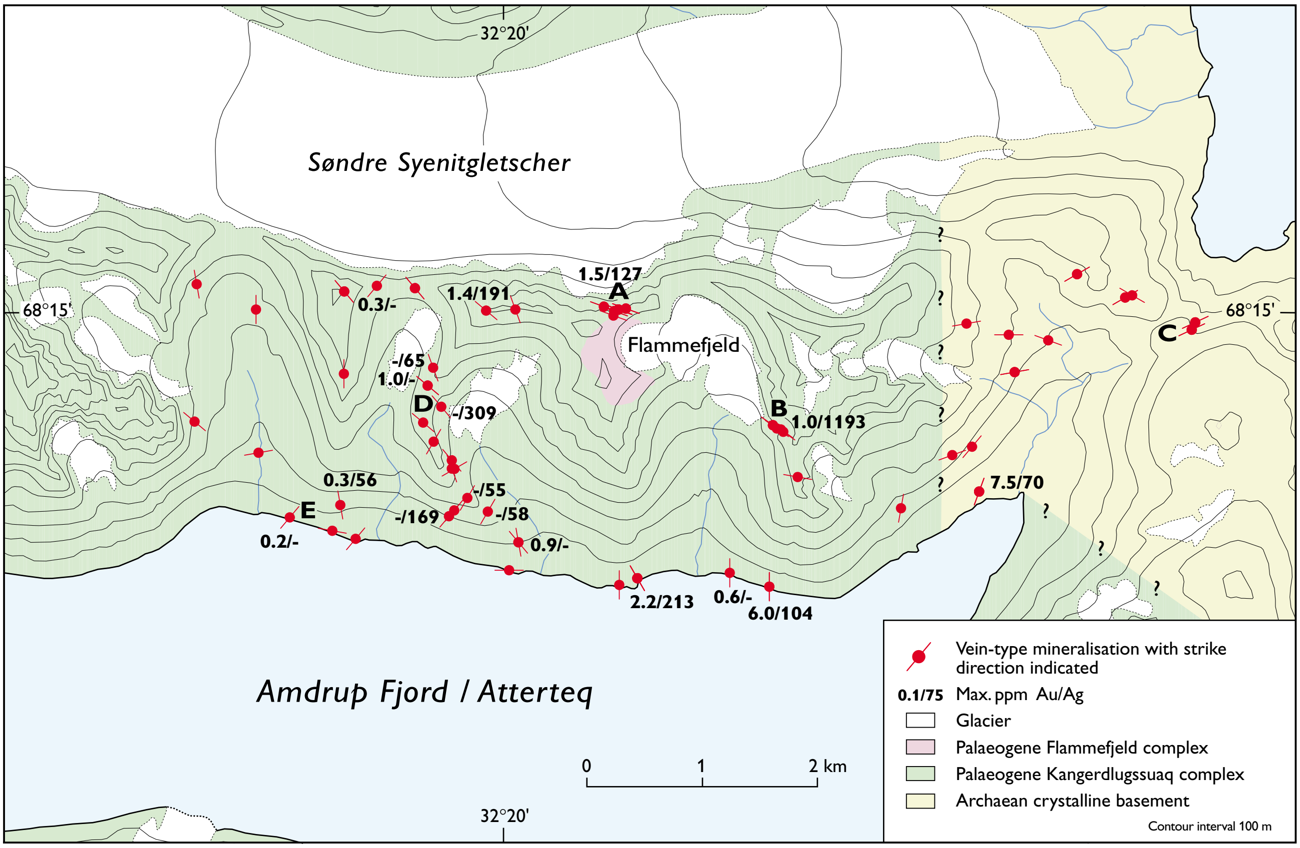

Fig. 2. Simplified geological map of the Amdrup Fjord area, showing occurrences of *in situ* vein-type mineralisation and localities **A–E**. Maximum gold and silver values are shown where Au > 0.1 ppm and Ag > 50 ppm. Bedrock geology based on Kempe *et al.* (1970), Geyti & Thomassen (1983) and Myers (1988).

intruded by magmatic rocks generated during the continental break-up of the North Atlantic in the Early Palaeogene (Wager 1934; Brooks & Nielsen 1982). The crystalline basement consists predominantly of quartzofeldspathic gneisses formed during a major late Archaean episode of sialic crust formation between 3.0 and 2.8 Ga ago (Taylor *et al.* 1992).

The Palaeogene magmatic rocks include extensive plateau basalts, several felsic and mafic alkaline intrusions and a major coast-parallel dyke swarm. The largest of the intrusions is the Kangerdlugssuaq complex located on the west side of the fjord Kangerlussuaq (formerly 'Kangerdlugssuaq'). This consists of the *c.* 50 Ma Kangerdlugssuaq alkaline intrusion and a number of both older and younger satellite intrusions (Fig. 1; Kempe *et al.* 1970; Brooks & Gill 1982; Nielsen 1987). The *c.* 700 km^2 Kangerdlugssuaq alkaline intrusion consists of concentric zones with gradational contacts of quartz syenite at the outside through syenite to nepheline syenite at the centre. The satellite intrusions include a variety of syenites and granites. The presumed youngest intrusive rocks comprise the 500 × 800 m sub-volcanic Flammefjeld complex which is intruded into quartz syenites at the contact between the Kangerdlugssuaq alkaline intrusion and younger satellite intrusions (Fig. 3). The Flammefjeld complex comprises a breccia pipe intruded by quartz porphyries and surrounded by a halo of hydrothermal alteration displaying vivid yellow and red oxidation colours; the name Flammefjeld translates as 'flame mountain' (Geyti & Thomassen 1984).

Mineral exploration by Nordisk Mineselskab A/S in 1970 and 1982 east and north of Flammefjeld revealed a number of base metal-bearing hydrothermal veins with enhanced silver and gold concentrations as well as stockwork-type molybdenum mineralisation in granitic breccia fragments of the Flammefjeld breccia pipe (Brooks 1971; Thomassen 1971; Geyti & Thomassen 1983, 1984; Brooks *et al.* 1987). The existence of a blind 'Climax-type' porphyry molybdenum deposit at 300–500 m a.s.l. below Flammefjeld, and 1–2 km below the palaeosurface, has been suggested (Geyti & Thomassen 1983; Stenstrop 1987). Hydrothermal veins of quartz-

Fig. 3. View to the west of 'Tågegang' (locality B) with Flammefjeld in the background to the left. For scale, note person clad in red (**arrowed**) collecting chip samples (GGU 456522, 23) over part of the *c.* 30 m wide vein structure.

carbonate cemented breccia are widespread in the Kangerlussuaq region, but tend to be barren outside the Amdrup Fjord area (Brooks 1972; Geyti & Thomassen 1983; Brooks *et al.* 1987).

Subsequently, the 'Ujarassiorit' annual minerals hunt programme managed by the Bureau of Minerals and Petroleum, Nuuk, Greenland, has received a number of gold-bearing rock samples from the area (Dunnells 1995). These samples are described as pyrite-bearing vein quartz with up to 24 ppm Au, often hosted by a basaltic wall rock; unfortunately, the precise sample localities are not known.

Preliminary results

During the field work all outcrops with visible *in situ* mineralisation were investigated and sampled. Where possible, 2–4 kg chip samples were collected across a mineralised structure; otherwise composite or selected grab samples were taken. Loose blocks with sulphides from either scree cones or local moraines were also sampled, and stream sediment samples and panned heavy mineral concentrates were collected from water courses. All samples were analysed for 49 elements by a combination of instrumental neutron activation and induc-

Table 1. Summary of selected elements for mineralised rock samples, Amdrup Fjord area

Type	Vein / *in situ* 82 samples / 40 localities			Vein / float 49 samples / 36 localities			Disseminated / *in situ* & float 22 samples / 18 localities		
	Range	Average	Median	Range	Average	Median	Range	Average	Median
Au ppb	< 2–7540	390	35	< 2–38400	1842	35	< 2–3430	186	15
Ag ppm	< 1–1193	59	6	< 1–687	55	10	< 1–47	4	< 1
Cu ppm	2–46670	1901	70	< 1–35150	1160	74	6–145	43	28
Pb ppm	< 3–431400	18786	1331	63–447200	32538	1773	< 3–10010	1082	125
Zn ppm	7–65510	6249	914	16–34220	4711	1506	11–5043	750	173
Bi ppm	< 2–628	47	5	< 2–91	7	< 2	< 2–121	10	3
Mo ppm	< 1–410	21	4	< 1–1430	69	4	< 1–31	7	5
As ppm	1–26700	1200	95	2–27500	979	149	2–1030	104	49
Sb ppm	< 1–4350	246	6	< 1–722	70	11	< 1–17	2	1
Mn ppm	55–> 100000	18877	4716	14–> 100000	24110	13430	26–11260	2949	1703
S %	0.01–25.73	4.00	1.39	0.02–16.93	3.32	1.74	0.29–12.09	2.98	2.01

Analyses by Activation Laboratories Ltd., Ontario, Canada.
Analytical methods:
Inductively coupled plasma emission spectrometry: Ag, Cu, Pb, Zn, Mo, Bi, S.
Instrumental neutron activation: Au, As, Sb, Mn (Fe).
Fire assay: Au > 100 ppb, Ag > 100 ppm and Pb > 2 pct.

tively coupled plasma emission spectrometry. Samples with > 0.1 ppm Au, > 100 ppm Ag, or > 2% Pb were subsequently assayed for these elements. The description below is based on field observations and analytical results.

Two types of mineralisation were observed and examined: (1) disseminated mineralisation, and (2) vein mineralisation. The known porphyry molybdenum mineralisation at Flammefjeld was not re-investigated during the 2000 field work.

1. Disseminated mineralisation

This type of mineralisation consists of pyrite disseminated in syenites; it is spatially and genetically related to the Flammefjeld intrusive complex which owes its conspicuous coloration to the oxidation of pyrite. The intensity of pyritisation diminishes away from the complex, and at about 1 km distance only isolated patches of pyrite-bearing syenite occur. Minor amounts of galena were noted in a few samples. Analytical results, summarised in Table 1, indicate that base metals and silver are low in this mineralisation type and only four samples returned more than 0.1 ppm Au. Of these, two samples with 3.4 ppm and 0.1 ppm Au respectively, stem from a > 10 m rusty outcrop west of Flammefjeld, near locality D (Fig. 2).

2. Vein mineralisation

Hydrothermal vein zones are widespread in both the syenitic and gneissic parts of the area within a distance of 5 km from Flammefjeld; some 40 *in situ* localities with this type of mineralisation were observed and sampled. Red-brown weathering colours of carbonates, black staining of manganese oxide and the intersection of brittle structures are useful guides to mineralisation. In the syenite area, mineralisation is nearly always located in cross-cutting dolerite dykes. These dykes are fine-grained, typically 1–3 m wide and steeply dipping with mainly NNW to NW trends.

The mineralised veins generally have widths in the cm–dm range. However, a few vein systems have widths in the metre range, and can be followed over distances of several hundreds of metres. The veins are typically developed as breccia fillings and crustifications of epithermal character, often displaying vuggy and colloform structures (cockade structures) (Fig. 4). Gangue minerals are quartz, calcite, Fe-Mn-Mg-carbonates and occasionally fluorite and barite. Galena is the most common ore mineral, followed by pyrite and sphalerite. Copper minerals (chalcopyrite and tetrahedrite-tennantite) are less common and arsenopyrite occurs sporadically. The sulphides occur as massive lenses and irregular seams of cm-thickness, and disseminated. Total sulphide concentrations rarely exceed 1% over the full width of the veins. The wall rocks exhibit silicification, carbonatisation, kaolinisation and phyllic alteration, with propylitic alteration of the mafic dykes.

The processes of brecciation, alteration and invasion of quartz, carbonates and sulphides affect the doleritic, syenitic or gneissic wall rocks to various degrees. The dolerites are typically asymmetrically mineralised, i.e. they are only mineralised on one side along the contact with unaltered syenite, and the ratios between fissure veins, cemented dyke rock breccias and unaffected dolerite wall rock are very variable. At some localities the entire width of a dyke is altered and mineralised; this is typically the case at the intersection of two or more dykes.

Vein mineralisation types and their metal concentrations

The vein mineralisation can be grouped into three types according to their dominant sulphides (Fig. 4):

1. Pyrite-bearing veins with typical widths in the cm–dm range. These predominate along the coast. The gold-bearing 'Ujarassiorit' samples (mentioned above) seem to be of this type.
2. Galena-sphalerite-pyrite veins. This is the most common type, and the largest outcrop encountered is the 30 × 200+ m 'Tågegang' of Geyti & Thomassen (1983; locality B, Figs 2, 3). The metal contents of two chip samples from locality B are given in Table 2, which also shows values from two other localities of this type (localities C, D).
3. Chalcopyrite-tetrahedrite-tennantite-pyrite ± galena ± sphalerite veins. These are only known from three outcrops and two boulder finds. The most prominent example is the 'Yellow Zone' of Geyti & Thomassen (1983), located at the northern margin of the Flammefjeld breccia pipe (locality A). This comprises a 50 × 200+ m vein swarm with individual vein thickness in the metre range (see Frontispiece of this volume, p. 3). Examples of chip sample values from this locality are given in Table 2.

Metal contents for 130 samples of vein-type mineralisation are summarised in Table 1. Gold concentrations above 0.1 ppm were recorded in 28% of these samples,

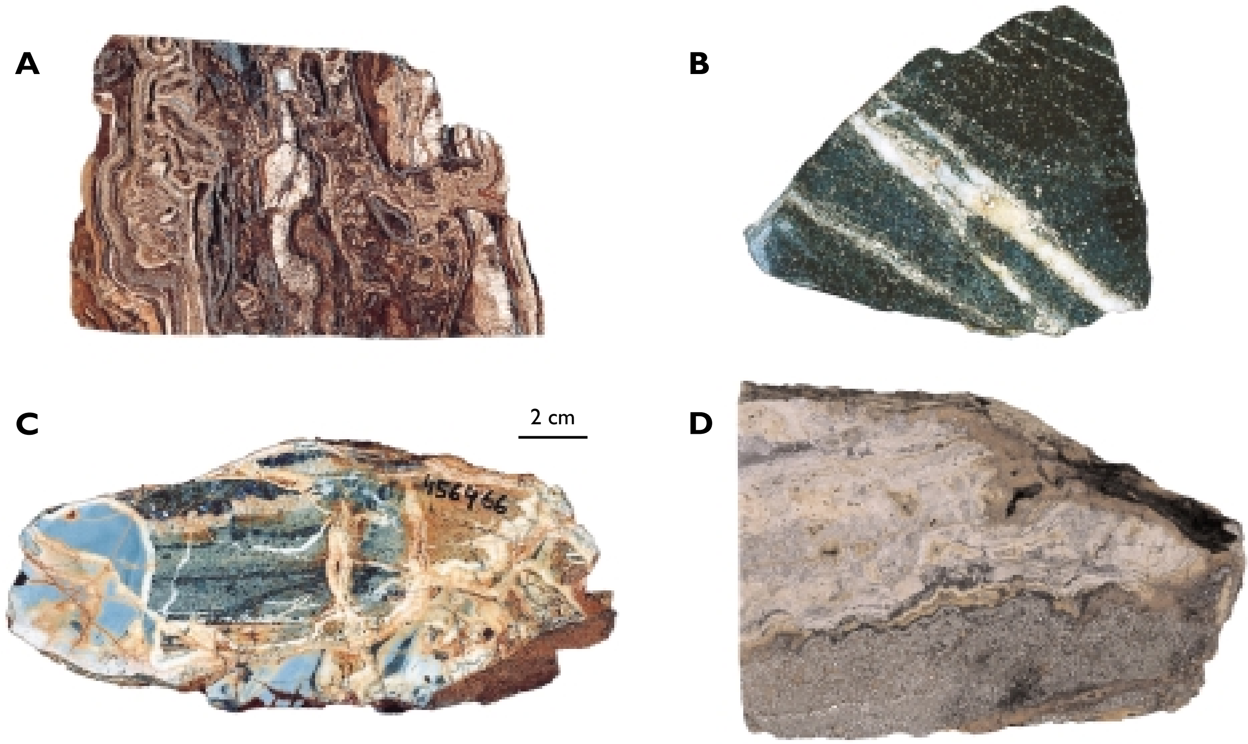

Fig. 4. Four hand-specimens showing typical vein mineralisation. **A**: Weathered surface of quartz-carbonate gangue displaying colloform structures. **B**: Cut surface of type (1) vein showing dolerite invaded by vein quartz and pyrite with 0.6 ppm Au and 37 ppm Ag. **C**: Cut surface of type (2) vein with brecciated structures (bluish chalcedony fragment to the left, bands of sulphides in the centre) and containing 14.4% Pb, 4.9% Zn and 309 ppm Ag. **D**: Cut surface of type (3) vein with seam of pyrite-chalcopyrite-tetrahedrite in quartz-carbonate gangue displaying colloform and vuggy structures, and with 1.5 ppm Au, 104 ppm Ag, 0.6% Cu, 0.5% Pb and 0.6% Zn. The scale bar is 2 cm. Photo: Jakob Lautrup.

while concentrations above 1 ppm were recorded in 12% with two maximum values of 38 ppm Au. Enhanced gold values are most common in vein types (1) and (3), and are often associated with copper, arsenic and bismuth, but rarely with silver. The Ag/Au ratio has a median of 200 for samples with > 0.1 ppm Au and/or > 50 ppm Ag. The overall distribution of gold and silver concentrations indicates that elevated values occur within a distance of 3–4 km from Flammefjeld, whereas low values characterise the gneisses to the east and the nepheline syenites to the west (Fig. 2).

The highest *in situ* gold values (up to 7.5 ppm) stem from vein types (1) and (3) along the coast south and south-east of Flammefjeld. The one maximum gold value of 38 ppm stems from a pyrite-arsenopyrite-bearing float collected near the coast 3 km south-west of Flammefjeld (locality E, Fig. 2). Together with other nearby auriferous type (1) floats and veinlets, the gentle slopes of this area constitute a worthwhile gold exploration target. The other maximum gold value stems from a strongly oxidised type (3) float collected on the glacier east of Flammefjeld just north-west of locality B. Two other nearby float samples returned 28 ppm and 2 ppm Au, respectively. Distinct vein structures occur in a steep cliff above the collection sites.

Silver concentrations above 50 ppm occur in 25% of the samples, values above 100 ppm in 15% and above 200 ppm in 8%; the maximum value recorded is 1193 ppm Ag. Silver correlates well with lead and is most common in vein types (2) and (3). The sample with 1193 ppm Ag stems from locality B ('Tågegang'). Locality B and floats just north-west of locality B account for seven of the eight samples which yielded silver values above 250 ppm. The eighth sample comes from locality D. Outcrop samples and float from a vein system 1 km east of locality E yielded 222 ppm, 169 ppm and 55 ppm Ag, whereas the previously reported high silver concentrations at locality C ('Wild Willys Vein', Brooks 1971) could not be confirmed (Table 2).

Average and median values in Table 1 indicate that Pb > Zn > Cu and thereby confirm the field observations. Lead values above 1% were returned from 25%

Table 2. Analytical values of selected chip samples, Amdrup Fjord area

Locality	A	A	B	C	D
GGU sample no.	456531	456538	456522–23	456401	456463
Length in m	5	4	10	5	1
Au ppm	1.03	0.34	0.21	0.05	0.05
Ag ppm	96	127	157	36	256
Ag/Au	93	374	748	720	5120
Cu%	1.51	0.78	0.03	0.02	0.03
Pb%	0.51	1.36	10.23	1.73	7.45
Zn%	0.57	3.23	0.98	0.08	1.66
Bi ppm	121	30	22	14	< 2
Mo ppm	245	108	2	7	5
Fe%	14.37	4.36	9.20	6.58	6.85
As%	0.26	0.19	0.01	0.01	0.02
Sb%	0.21	0.32	0.02	< 0.01	0.02
S%	13.79	5.73	2.44	0.29	2.39
Mn%	3.73	0.47	6.85	1.64	0.85

Analyses: details as for Table 1. Localities are shown on Fig. 2.

of the samples, zinc values above 1% were returned from 17%, and copper values above 1% were returned from 5%. The vein-type mineralisation is also characterised by relative high manganese concentrations, and occasionally elevated arsenic, antimony, molybdenum and bismuth (see Table 1).

Concluding remarks

Prior to the field work in 2000, five hydrothermal vein systems were known from the Amdrup Fjord area; during the summer an additional 35 veins, albeit mostly of modest size, were found. We assume that several more could have been found given more time, and we conclude that mineralisation is surprisingly widespread around Flammefjeld.

The vein-type mineralisation centred on Flammefjeld is confined to brittle structures and shows similarities with epithermal gold-silver veins of low-sulphidation type generated at shallow depths, i.e. within *c.* 1.5 km of the Earth's surface (see e.g. Sillitoe 1993). Porphyry-type deposits, like that proposed below Flammefjeld (see above), are often accompanied by distal base metal veins enriched in precious metals, as is the case in the investigated area, and a genetic relationship between the two is likely. No distinct hydrothermal zoning centred on Flammefjeld was observed for the vein-type mineralisation, but proximal copper – distal lead is indicated, and the predominance of pyrite over galena along the shore of Amdrup Fjord also suggests a vertical pyrite-galena zonation. No obvious preferred orientation of the mineralised veins could be identified, but an ongoing structural study based on LANDSAT images and aerial photographs aims to investigate this issue further. The vein-type mineralisation which was encountered is unlikely to yield economic base metal deposits, but does have a potential for gold and silver. Among the proposed targets for further exploration are the coast south-east of Flammefjeld and the sub-areas designed as A, B, D and E on Fig. 2.

The reconnaissance project centred on the Amdrup Fjord region and Flammefjeld will be concluded with a report including sample descriptions, locality maps and chemical analyses. The results from this project will be incorporated in the Survey's assessment of the regional ore potential in the Palaeogene igneous province of East Greenland.

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The East Greenland continental margin, the Prinsen af Wales Bjerge and new Skaergaard intrusion initiatives

Troels F.D. Nielsen, Henriette Hansen, C. Kent Brooks, Charles E. Lesher and field parties

The rifted volcanic margin of East Greenland has remained a major area for field studies and the development of models for the dynamics of plume-related continental break-up since the start of the Danish Lithosphere Centre (DLC) in 1994. The studies cover a range of disciplines and geological processes from the early development of pre-break-up basin formation and sedimentation over the main phase of basaltic magmatism to the late stages of alkaline magmatism and structural re-equilibration.

The East Greenland field activities in the summer of 2000, collectively referred to as *EG 2000*, were facilitated by a logistic platform provided by support from Statens Naturvidenskabelige Forskningsråd (SNF, the Danish Natural Science Research Council) and the Bureau of Minerals and Petroleum (BMP) in Nuuk, Greenland for the retrieval of 6 km of drillcore from the Skaergaard intrusion. During 1989 and 1990 mineral exploration had resulted in drilling of more than 15 km of core through the classic layered gabbros. The logistic platform also provided support for DLC and Geological Survey of Denmark and Greenland (GEUS) field work and projects throughout the Kangerlussuaq region and on the Blosseville Kyst (Fig. 1), as well as mineral exploration and petroleum company activities.

Study region, field parties and logistics

EG 2000 operated from 19 July to 28 August 2000 out of a base in Sødalen (Fig. 1), where a 600 m long STOL air strip and base facilities, including two huts, had been established between 1982 and 1990. During the first week of the operation a four-man team packed and air-freighted Skaergaard drillcore to Iceland. Return flights to Greenland were used for the transport of equipment, and from 25 July and onwards for field parties. The field operations were supported by an Aerospatial AS350 B2 helicopter and additional transport was provided by a wooden boat and a rubber dinghy.

The personnel involved in *EG 2000* and their affiliations are listed in Table 1. The main areas of activity (Fig. 1) included:

1. Studies of plateau basalt successions (C.E.L., C.T., L.H., J.S., see Table 1), the Borgtinderne syenite intrusions (P.K., S.B.), the newly discovered ultramafic Ejnar Mikkelsen intrusion (P.K., S.B.), and a regional swarm of lamprophyre dykes with mantle nodules in the area between Savary Fjord and Wiedemann Fjord on the central part of Blosseville Kyst and inland as far as Borgtinderne (P.K., S.B.).
2. Studies of inland plateau basalt successions in Prinsen af Wales Bjerge (H.H., A.K.), and at Tjældebjerget (H.H., A.K., L.H., C.E.L.).
3. Studies of the pre-basaltic sedimentary basin between Sødalen, inland and along Christian IV Gletscher (M.L., M.B., S.O., T.N.; see also Larsen *et al.* 2001, this volume).
4. Correlation of plateau basalt formations across Nansen Fjord and towards Kangerlussuaq in the coastal area between Nansen Fjord and Miki Fjord (M.G., L.H., C.E.L.).
5. Systematic sampling of profiles and field investigations in the Skaergaard intrusion on the eastern shore of Kangerlussuaq (C.E.L., P.T., C.T., A.F., J.J., J.S.) and a reconnaissance gravimetry programme over the intrusion (C.K.B., M.K.).
6. Regional sampling of the Kangerdlugssuaq alkaline intrusion and the Astrophyllite Bay complex on the western side of Kangerlussuaq (C.K.B., D.W.P., M.S.R.).
7. Investigation and sampling of disseminated and vein-related Au-Ag mineralisations in the Amdrup Fjord – Søndre Syenite Gletscher area on the west side of Kangerlussuaq (B.T., J.D.K.; see also Thomassen & Krebs 2001, this volume).

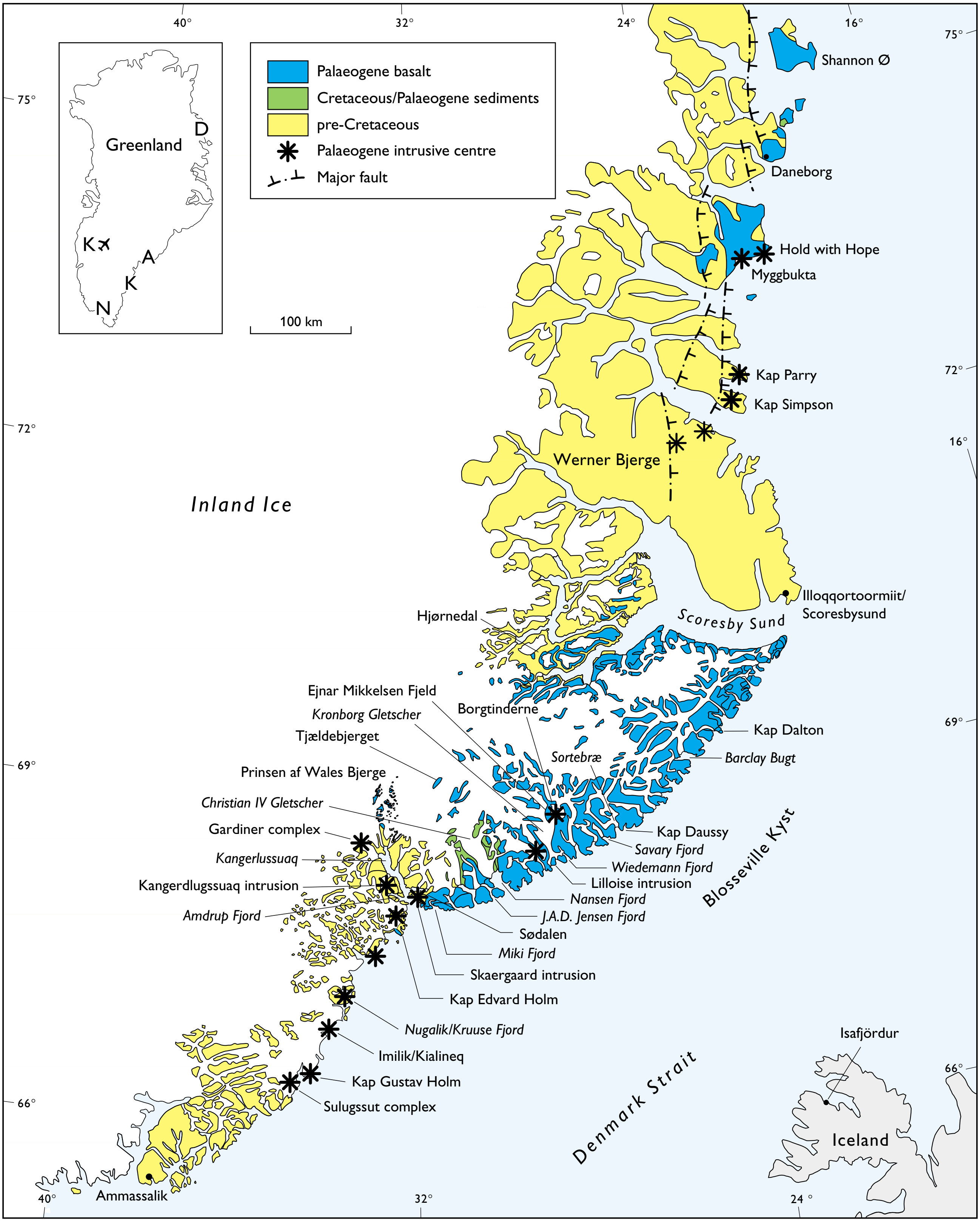

Fig. 1. Map of the Palaeogene East Greenland igneous province. 'Astrophyllite Bay' is located on the north shore of outer Amdrup Fjord. Insert map abbreviations – **A**: Ammassalik; **D**: Danmarkshavn; **K**: Kassortoq; **N**: Narsarsuaq and **K✈**: Kangerlussuaq / Søndre Strømfjord. Modified after Brooks & field parties (1996).

8. Establishment of seismic stations in Sødalen, Hjørnedal in the inner Scoresby Sund fjord system (70°N) and in Singertat intrusion in Kassortoq fjord *c.* 300 km south of Ammassalik (O.G.).
9. Selection, packing and transport of 16 tons of research core and 4 tons of exploration core from the Skaergaard intrusion to the Geological Museum in Copenhagen and to the BMP core library in Kangerlussuaq / Søndre Strømfjord, West Greenland (T.F.D.N., J.G., C.E.L., J.S.).

Pre-basaltic basin development and sedimentation

Since the early description of the 'Kangerdlugssuaq Sedimentary Series' (now Kangerdlugssuaq Basin) by Wager & Deer (1939) and Wager (1947), the pre-basaltic sediments have received periodic attention by a number of research groups (e.g. Soper *et al.* 1976a, b; Nielsen *et al.* 1981; Larsen, M. *et al.* 1996, 1999). Taking the view that the development of the sedimentary basin and its structural evolution is an integrated part of the continental break-up process, the sedimentary studies in the Kangerlussuaq region may provide important constraints for the models of plume impingement and the dynamics of the break-up process.

The summer 2000 field work (see Larsen *et al.* 2001, this volume) focused on sedimentology, biostratigraphy and diagenesis. Special attention was paid to: (1) sedimentology and ammonite biostratigraphy in a coarse-grained Lower Cretaceous succession forming the lowermost sedimentary unit in the area; (2) sampling of a mudstone succession of presumed Upper Cretaceous age in order to improve the existing biostratigraphy; and (3) detailed studies of the transition between sediments and the earliest volcanic succession. In addition a number of sections were sampled in order to illustrate the influence of intrusions on sandstone diagenesis.

In connection with GEUS field work, a group of sedimentologists and geophysicists from the oil industry visited Sødalen. The group focused on the possibility of using the sediments of the Kangerlussuaq Group (Larsen *et al.* 1996) as an outcrop analogue for basin evolution in the offshore areas around the Faeroe Islands. A number of key sections were visited and the sedimentological and sequence stratigraphic models discussed with Survey personnel. The excursion was led by L. Hamberg, Dansk Olie og Naturgas (DONG).

Table 1. List of participants and institutions with abbreviations

Institutions

AU	Aarhus Universitet (Aarhus University), Århus, Denmark.
BMP	Bureau of Minerals and Petroleum, Nuuk, Greenland.
DLC	Danish Lithosphere Centre, Copenhagen, Denmark.
GEUS	Danmarks og Grønlands Geologiske Undersøgelse (Geological Survey of Denmark and Greenland), Copenhagen, Denmark.
KMS	Kort & Matrikelstyrelsen (National Survey and Cadastre, Denmark), Copenhagen, Denmark.
KU	Københavns Universitet (University of Copenhagen), Copenhagen, Denmark.
NGU	Norges Geologiske Undersøgelse (Geological Survey of Norway), Trondheim, Norway.
SNF	Statens Naturvidenskabelige Forskningsråd (Danish Natural Science Research Council), Copenhagen, Denmark.
UCD	University of California Davis, Davis, USA.

Participants and contributors

A.F.	Anja K.M. Fonseca	KU/DLC
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C.E.L.	Charles E. Lesher	UCD
C.K.B.	C. Kent Brooks	KU/DLC
C.T.	Christian Tegner	NGU/DLC
D.W.P.	David W. Peate	DLC
H.B.	Haukur Brynjólfsson	University of Iceland, Iceland
H.H.	Henriette Hansen	DLC/GEUS
J.D.K.	Johan Ditlev Krebs	GEUS
J.G.	Jens Gregersen	GEUS
J.J.	Jakob K. Jakobsen	KU/DLC
J.S.	Joel A. Simpson	UCD
L.H.	Lara Heister	Stanford University, USA
M.B.	Morten Bjerager	KU
M.G.	Michelle Gras	UCD
M.K.	Mette Kristensen	AU
M.L.	Michael Larsen	GEUS
M.S.R.	Morten S. Rishuus	AU
O.G.	Olafur Gudmundsson	DLC
P.B.	Palle Bay	GEUS
P.K.	Peter Kelemen	Woods Hole Oceanographic Inst. USA
P.T.	Peter Thy	UCD
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Palaeogene flood basalts

A dominant field of DLC research is the temporal and spatial chemical variations of East Greenland flood basalts (Fig. 1). These studies provide the chemical basis for the modelling of melting regimes, mantle dynamics and plume involvement in the process of continental break-up in the North Atlantic *c.* 60 million years ago. The volcanic activity lasted from 61 Ma to

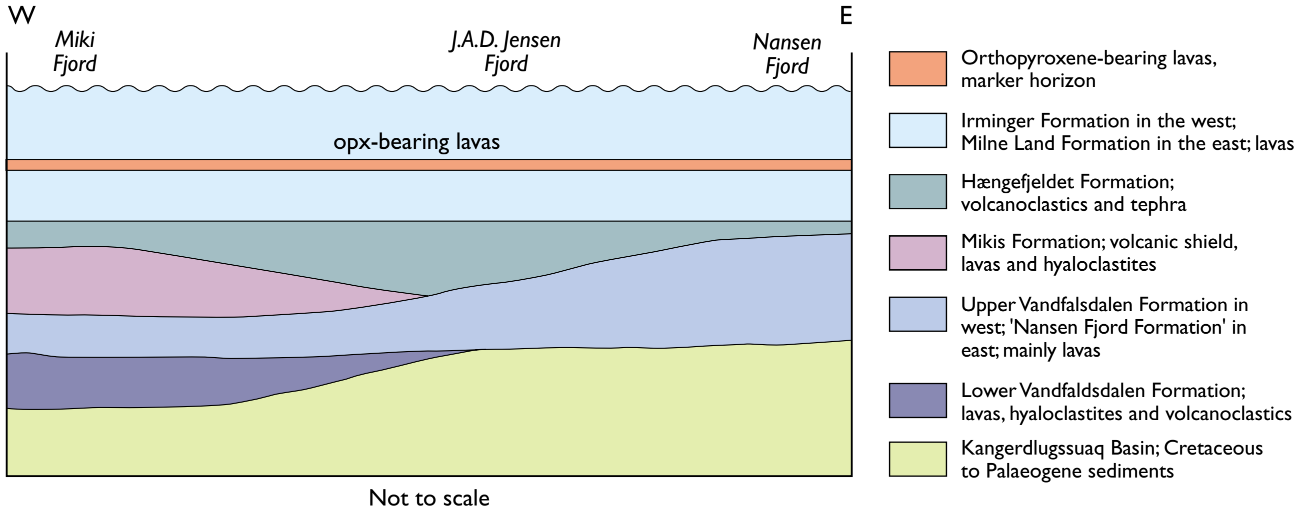


Fig. 2. Schematic correlation from Miki Fjord over J.A.D. Jensen Fjord to the east shore of Nansen Fjord, based on *EG 2000* results and previous observations.

13 Ma, but was episodic and most intense from *c.* 56 to 54 Ma (Storey *et al.* 1996a, b). The total volume of extruded magma places East Greenland amongst the largest onshore volcanic provinces on Earth (e.g. Coffin & Eldholm 1994; Eldholm & Grue 1994; Mahoney & Coffin 1997). Due to Oligocene uplift, the Coast Parallel Flexure of East Greenland (Nielsen & Brooks 1981) and post break-up tilting of the successions, a more than 8 km thick succession of lavas can be studied in great detail.

Stratigraphic and geochemical studies in the northern part of the province had identified a number of basaltic formations (e.g. Larsen *et al.* 1989). A combination of photogrammetric and geochemical methods have made it possible to trace these formations throughout the entire province, which testifies to the uniformity of the magmatism along the East Greenland continental margin (Brooks & field parties 1996; Pedersen *et al.* 1997; Tegner *et al.* 1998a; Larsen, L.M. *et al.* 1999). The tight stratigraphic and radiometric age control allows studies of the lateral geochemical variation within individual formations, and the inland chemical variation which supposedly reflects the effects of an increasingly thick continental lid (Fram & Lesher 1997; Tegner *et al.* 1998b). The *EG 2000* field operations – like those of 1995 (Brooks & field parties 1996) – focused on the sampling and study of strategically located profiles in the > 8 km thick flood basalt succession along the Blosseville Kyst; the regional field programme was completed during the summer of 2000.

The Lower Basalts in the Kangerlussuaq region (C.E.L., L.H., M.G.)

The Lower Basalts of the Kangerlussuaq region were established as a separate part of the volcanic province by L.R. Wager and coworkers (e.g. Wager 1947). Complex stratigraphy and a wide geochemical range (Brooks & Nielsen 1982a) have made it difficult to correlate the Lower Basalts with the prevalent and more uniform tholeiitic plateau basalts to the north and east. Over the years, several correlation schemes have been proposed (e.g. Nielsen *et al.* 1981; Larsen *et al.* 1989), but without the necessary stratigraphic control. The general stratigraphy and structure of the Lower Basalts have been described by Nielsen *et al.* (1981), Hansen & Nielsen (1999) and Ukstins (2000), but the correlation with the regional plateau basalt formations originally identified in the Scoresby Sund region (Larsen *et al.* 1989) has remained unresolved.

The identification of a suite of orthopyroxene-bearing marker flows in the Milne Land Formation on the eastern shores of Nansen Fjord (Fig. 1), and correlation with similar flows on the peninsula between J.A.D. Jensen Fjord and Nansen Fjord, suggests the possibility of a lithological correlation to the type area of the Lower Basalts in the Miki Fjord area. The orthopyroxene-bearing lavas have now also been sampled in the lower part of the plateau basalts (the Irminger Formation of Nielsen *et al.* 1981) overlying the Lower Basalts on the south shore of inner Miki Fjord and these studies show that the Irminger Formation is identical with the Milne Land Formation (see also Larsen, L.M. *et al.* 1999).

The eastward correlation of the formations of the Lower Basalts in the Miki Fjord area (Fig. 1) suggests that the Lower Vandfaldsdalen Formation and Mikis Formation are only locally developed volcanics (Fig. 2). These two formations include the characteristic TiO_2-rich picrite lavas of the Lower Basalts (Nielsen *et al.* 1981; Brooks & Nielsen 1982a, b; Fram & Lesher 1997; Hansen & Nielsen 1999). No equivalents to the wide variety of the Lower Vandfaldsdalen Formation volcanics have been observed towards the east in the Ryberg Fjord and J.A.D. Jensen Fjord area (Fig. 1), whereas the Upper Vandfaldsdalen Formation can be followed eastwards to the shores of Nansen Fjord. The Mikis Formation seems to represent a volcanic structure, probably a shield volcano (Ukstins 2000), between the Upper Vandfaldsdalen Formation and the overlying tuffs and volcanoclastic sediments of the Hængefjeldet Formation.

The variably sorted tephra deposits between the Milne Land Formation and the informal 'Nansen Fjord Formation' on the east shores of Nansen Fjord (Larsen, L.M. *et al.* 1999), like the equivalent deposits in J.A.D. Jensen Fjord, show no signs of reworking and provide a correlation across the fjord, and there is no compelling evidence at this location for a major hiatus between the eruption of the Lower Basalts and the overlying plateau basalts as proposed by Larsen, L.M. *et al.* (1999). The correlation of the tephra deposits indicates that lavas assigned to the 'Nansen Fjord Formation' on the east side of Nansen Fjord (Larsen, L.M. *et al.* 1999) are equivalent to lavas of the Vandfaldsdalen Formation on the west side of Nansen Fjord (Fig. 2), and this suggests that no new formation needs to be formalised.

Spatial distribution of magma types in the plateau basalts (C.E.L., C.T., J.S., L.H.)

Tegner *et al.* (1998b) identified three main geochemical groups of lavas in the 'Master Profile' through the plateau basalts of the Blosseville Kyst: (1) depleted MORB type lavas, (2) the common Fe-Ti tholeiites and (3) high-Ti tholeiites. All of these occur in the Rømer Fjord Formation of the 'Master Profile', but the coexistence of three types of lava formed under very different conditions of melt generation is not easily understood (Tegner *et al.* 1998b).

At the stratigraphic level of the Rømer Fjord Formation the 'Master Profile' is compiled from inland and coastal profiles, and the coexistence of all three geochemical types could be an artefact of the compilation strategy. Resampling and new profiles in the Savary Fjord area (Fig. 1) in summer 2000 suggest that coexistence of the three magma types reflects a lateral variability with MORB types and Fe-Ti basalts in coastal profiles, and Fe-Ti basalts and high-Ti basalts in inland profiles. This would be in better conformity with models of rifting and thinning of the continental crust along the coast of East Greenland.

The Prinsen af Wales Bjerge and Tjældebjerget (H.H., A.K.)

The Prinsen af Wales Bjerge (Fig. 1) consist of a series of inland nunataks, where only few investigations have hitherto been made. The stratigraphical relationship between the Prinsen af Wales Bjerge volcanics and the main exposures of East Greenland flood basalts is poorly known. The present account, based on summer 2000 field work, represents the first detailed description of the volcanic successions in the northern part of the area.

Tholeiitic compositions dominate the entire East Greenland province (e.g. Brooks & Nielsen 1982a, b; Larsen *et al.* 1989), but in the Prinsen af Wales Bjerge (Fig. 1) tholeiitic volcanism was succeeded by eruption of alkaline lavas (Wager 1947; Anwar 1955; Hogg *et al.* 1988, 1989; Brooks & field parties 1996; Brown *et al.* 1996). The main purpose of the summer 2000 field work in the Prinsen af Wales Bjerge area was to determine stratigraphical relationships in the nunatak suite, and to stratigraphically connect the area with the areas investigated during the 1995 DLC field campaign (Brooks & field parties 1996).

The oldest volcanics of the Prinsen af Wales Bjerge (Fig. 3) are located furthest south at Urbjerget (Wager 1947). They are tholeiitic and are intercalated with epiclastic and volcanogenic sediments overlying the Archaean tonalitic gneiss basement. The lowermost *c.* 61 Ma old flows and sediments are part of the new, not yet formalised 'Urbjerget Formation', whereas the overlying 57 to 55 Ma tholeiitic flows are part of the regionally widespread Milne Land Formation. The flows of the 'Urbjerget Formation' and Milne Land Formation dip at 1–2° NNW. The southernmost exposures of alkaline lava flows at '1982 Nunatak' have highly variable dips, probably reflecting proximity to palaeo-eruption sites, but further north the alkaline lavas regain regional dips of 1–2° NNW. This suggests that progressively younger lavas are exposed northwards in the Prinsen af Wales Bjerge. An alkaline extrusive in a volcanic cone structure enclosed in the succession has been dated to 52.5 ± 0.3 Ma (Peate *et al.* 2000), but the age span of the

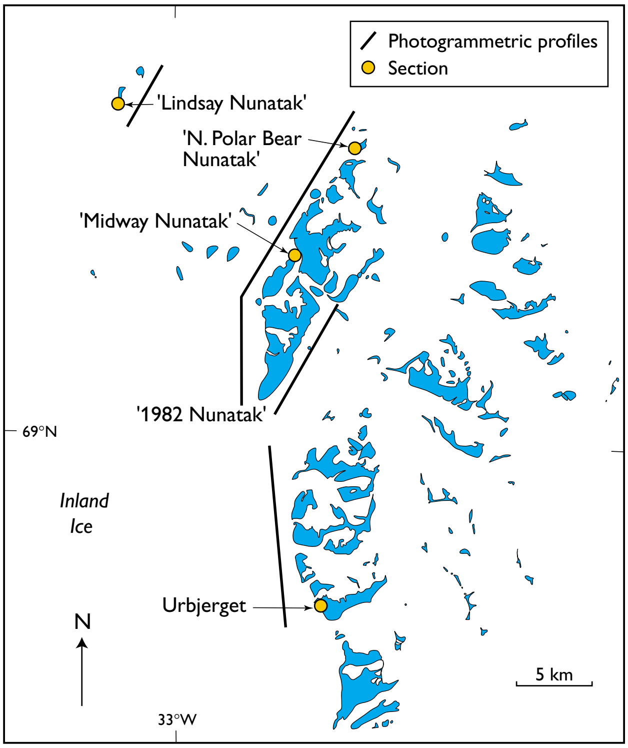


Fig. 3. Prinsen af Wales Bjerge with place names used in text, photogrammetric lines and profile/sampling sections. For regional location of Prinsen af Wales Bjerge, see Fig. 1.

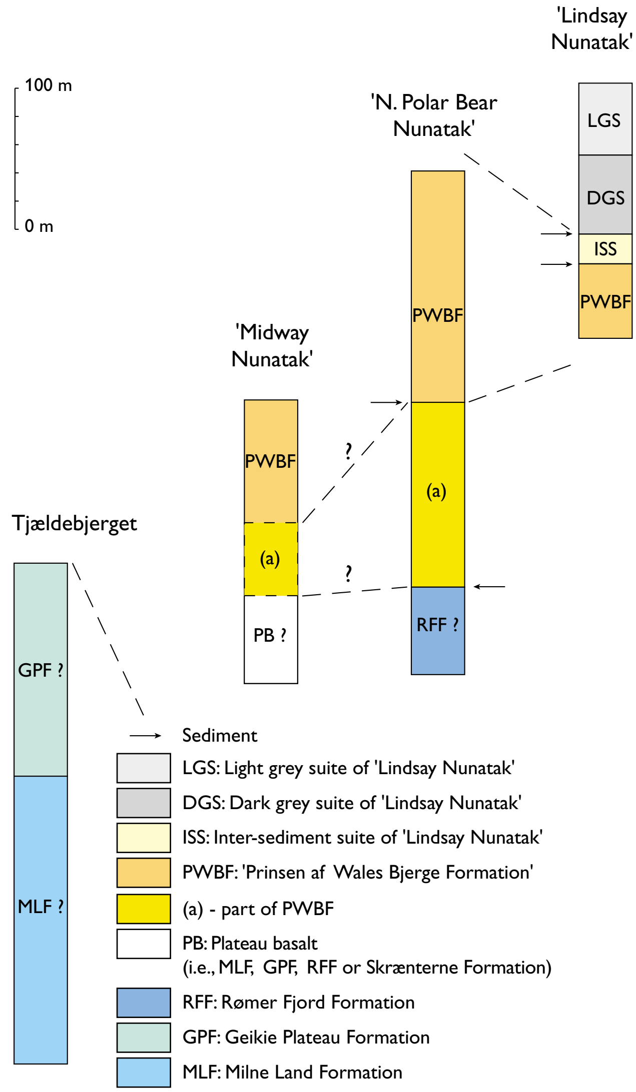
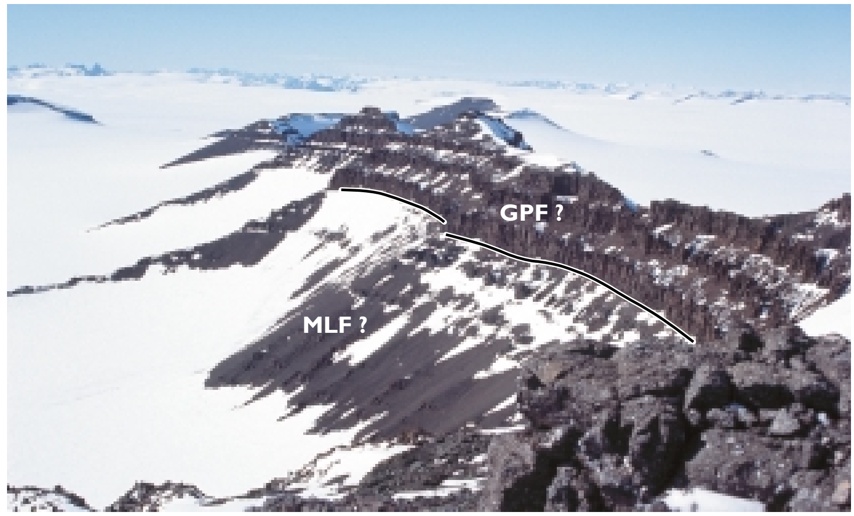


Fig. 4. Correlation of profiles measured in Prinsen af Wales Bjerge, and comparisons with Tjældebjerget profile. The correlation is mainly based on photogrammetry and field observations, with support from geochemical whole-rock analyses and $^{40}Ar/^{39}Ar$ ages of some 'Lindsay Nunatak' flows.

alkaline volcanism has not yet been established in detail. Photogrammetry was used for identification of four locations, Tjældebjerget, 'Lindsay Nunatak', 'N. Polar Bear Nunatak' and 'Midway Nunatak', where studies of sections through the volcanic succession would provide critical new stratigraphical information and samples suited for geochemical investigations (Figs 3, 4). In addition, Urbjerget was briefly visited to examine the border zone between the 'Urbjerget Formation' and Milne Land Formation.

Tjældebjerget. This nunatak is in a key position between the stratigraphically well-known flood basalt successions of the north-eastern Blosseville Kyst and the Prinsen af Wales Bjerge (Fig. 1). The lowermost *c.* 100 m of the profile (Fig. 5) consists of less than 5 m thick aphyric and olivine-phyric pahoehoe flows and thicker (up to 19 m), massive, highly plagioclase-phyric flows (probably suitable for ^{40}Ar-^{39}Ar dating). The overlying 110 m of the sequence is dominated by up to 10 m thick aphyric and sparsely olivine-plagioclase-pyroxene-phyric flows. Red tuffaceous beds up to 50 cm thick occur commonly. The uppermost 180 m is formed by a succession of aphyric to sparsely phyric, 10 to 30 m thick flows with massive, columnar-jointed lower parts and rubbly flow tops. Red volcanoclastic sediments with thicknesses of 10 to 20 cm are found on top of all thick and massive flows. The top of the nunatak consists of *c.* 15 m of olivine-phyric, vesicular, 0.5 to 1.0 m thick pahoehoe type flows. Based on the petrographic characteristics and photogrammetric observations, the lowermost part of the succession may correlate with the regionally distributed Milne Land Formation, and the upper 180 m with the Geikie Plateau Formation (Fig.

Fig. 5. Tjældebjerget profile locality looking west. The height of the profile is *c.* 300 m, with top of the profile at 2650 m altitude. The suggested Milne Land Formation – Geikie Plateau Formation contact is shown by the **black line**.



4). However, these suggested correlations await confirmation by geochemistry and age determinations.

'Lindsay Nunatak'. The most north-westerly exposures in the Prinsen af Wales Bjerge are found on 'Lindsay Nunatak' and a smaller exposure north of 'Lindsay Nunatak' proper (Fig. 3). These exposures are believed to show the youngest volcanics of the region. 'Lindsay Nunatak' was briefly visited in 1995, and found to comprise alkaline flows of the 'Prinsen af Wales Bjerge Formation' overlain by conglomerates and sediments, and followed in turn by olivine-rich tholeiitic lavas. Further detailed stratigraphical and geochemical sampling was carried out in summer 2000.

A > 5 m thick, sparsely pyroxene-phyric alkaline basalt flow (Table 2) forms the base of 'Lindsay Nunatak'. Gravel slopes above the flow expose abundant fragments of silicified wood, and tuffaceous rock fragments containing silicified wood. The lowest outcrop above the lowermost flow is a polymict, matrix-supported conglomerate with well-rounded, but poorly sorted clasts ranging in size from *c.* 1 to 30 cm. The clasts are mainly porphyritic extrusives, together with a wide variety of intrusive rock types including highly alkaline eudialyte-bearing syenite and alkaline pyroxenites reminiscent of the lithologies at the Gardiner complex (see also Brooks & field parties 1996). The conglomerate con-

Table 2. Selected major element analyses of lava flows from 'Lindsay Nunatak', Prinsen af Wales Bjerge

Sample*	458931	458932	458933	458941	458948
Suite**	PWBF	ISS	ISS	DGS	LGS
	mela-nephelinite	mela-nephelinite	basanite	tholeiite	olivine tholeiite
SiO_2	37.45	42.35	46.03	47.97	49.76
TiO_2	7.82	4.28	3.31	2.88	1.61
Al_2O_3	7.40	6.34	8.53	10.55	11.34
Fe_2O_3	11.02	5.70	4.43	6.92	3.13
FeO	5.57	9.48	9.67	6.44	8.02
MnO	0.26	0.20	0.20	0.19	0.17
MgO	6.67	15.91	13.18	8.78	12.73
CaO	15.53	10.17	10.08	10.06	9.54
Na_2O	2.53	1.59	1.99	2.50	2.05
K_2O	1.35	1.02	0.68	0.77	0.55
P_2O_5	1.17	0.44	0.36	0.34	0.16
Vol.	2.55	1.67	1.07	2.05	0.88
Sum	99.32	99.15	99.52	99.44	99.95

* GGU sample number. XRF analyses on glass discs by GEUS.
** See Fig. 4 for identification of suite.

tains 30 × 200 cm cross-bedded sandy lenses, elongated parallel to the base of the conglomerate, and is probably a river deposit. Two 10 to 20 m thick olivine and olivine-pyroxene-phyric columnar-jointed flows with massive flow bases and rubbly flow tops (ISS in Fig. 4) separate the lower sediments from a second polymict conglomerate. The latter contains 10 to 30 cm rounded clasts at its base overlain by a yellow volcaniclastic, redeposited (?), sediment with black and red scoria, light grey coloured pumice, and fresh euhedral crystals of feldspar and pyroxene up to 15 mm across. The upper polymict conglomerate is overlain by a 50 m thick succession of dark grey olivine-phyric pahoehoe flows (DGS in Fig. 4) with an average unit thickness of about 50 cm, followed by *c.* 65 m of light grey, olivine-phyric pahoehoe flows (LGS in Fig. 4) that extend to the top of the nunatak.

'N. Polar Bear Nunatak'. This nunatak is located east of 'Lindsay Nunatak' in the northernmost part of the Prinsen af Wales Bjerge (Fig. 3). Photogrammetric studies and the geochemistry of lavas in a parallel section to the south (Peate *et al.* 2000) suggest that the exposed flows belong to the not yet formalised 'Prinsen af Wales Bjerge Formation'. The nunatak was targeted for sampling because pre-field work photogrammetry identified a distinct succession of thin (< 20 m) flows bounded by tuffaceous or soil horizons ('a' in Fig. 4). Succession 'a' may be used for the subdivision of the 'Prinsen af Wales Bjerge Formation' and could prove useful for constraining the timing of volcanism.

Below succession 'a' is exposed a *c.* 50 m thick aphyric basalt, which may belong to the Rømer Fjord Formation (Fig. 4; D.W. Peate, personal communication 2000); a 20 cm thick red volcanoclastic sediment above the aphyric basalts forms the lower boundary of 'a'. The lower part of succession 'a' consists of sparsely olivine-clinopyroxene-phyric 0.5–6 m thick flows, some of which are highly vesicular, red-weathering pahoehoe types. These very thin flows are replaced by thicker, 10–20 m, compound flows with massive bases and associated vesicle-filled pipes up to 10 cm in diameter and from *c.* 20–100 cm in vertical length. In the upper *c.* 30 m of succession 'a', flows are again thinner (2–4 m). Succession 'a' is overlain by dark coloured, brecciated volcanics intermixed with red volcanoclastic sediments, which may have formed near eruption centre(s) or as a result of hydraulic fragmentation of hot flows. The brecciated unit is followed by a *c.* 80 m thick succession of *c.* 5 m thick, compound olivine-clinopyroxene-phyric flows. A red tuff marks the base of a succession of thick massive flows that continues for a further 80 m to the top of the nunatak.

'Midway Nunatak'. South of 'N. Polar Bear Nunatak', a nunatak designated 'Midway Nunatak' was selected for sampling in order to determine the regional extent of succession 'a'. Here, the lower part of the succession consists of three massive 20–30 m thick flows that most likely belong to one of the regional plateau basalt formations, i.e. Milne Land, Geikie Plateau, Rømer Fjord or Skrænterne formations. These flows are interlayered with < 0.5 m thick red volcanoclastic sediments. The two lowermost flows are aphyric, whereas the third is olivine-pyroxene-phyric. Most of the remaining flows in the profile are relatively thin (less than 10 m), highly olivine-phyric, pyroxene-phyric or olivine-pyroxene-phyric flows, forming part of the 'Prinsen af Wales Bjerge Formation'. One exception is a rather thick (*c.* 30 m) massive flow at the top of the profile. Field observations cannot clearly identify the presence of succession 'a' at 'Midway Nunatak' which is tentatively indicated in Fig. 4. Chemical analyses are needed for a more thorough evaluation of the section.

Urbjerget. At Urbjerget (Fig. 3) a mudstone containing sparse, 3–7 cm rounded clasts was observed between the flow successions dated at 61 Ma and 57–55 Ma, respectively. The presence of these sediments supports the existence of a hiatus in the earliest stages of Palaeogene volcanism in this inland region, as has been suggested by Storey *et al.* (1996a) amongst others.

New Skaergaard intrusion initiatives

The 55 Ma old Skaergaard intrusion is associated with and emplaced into the base of the Palaeogene flood basalt succession of the East Greenland volcanic rifted margin. In this classic intrusion layered cumulates provide a complete record of extreme igneous fractionation of basaltic magma (Wager & Deer 1939). The excellent exposures (Fig. 6) and petrographic studies over the past 70 years have provided key observations for universal models of igneous differentiation (Wager & Brown 1968; McBirney 1996; Irvine *et al.* 1998). However, despite or perhaps because of the extensive studies and the wealth of information available, many features of the gabbros continue to be debated, and the Skaergaard intrusion remains a primary natural laboratory for crystallisation and fractionation models for basaltic magma.

Fig. 6. The spectacular magmatic layering in the UZa (Upper Zone a) Skaergaard intrusion gabbros in the Hjemsted Bugt area (located in Skaergaard intrusion on Fig. 1).

The recognition of the Skaergaard intrusion as a world-class palladium deposit (Bird *et al.* 1991; Andersen *et al.* 1998; Nielsen 2001) adds to the interest for a better understanding of its origin and development. From 1989 to 1990 drillcores > 1000 m long were recovered from the upper part of the Layered Series of the intrusion. They provide unprecedented opportunities for analysis and quantitative modelling. The cores are now available for research projects (see below), and this has led to new research initiatives in a collaborative effort between DLC, GEUS, the University of Copenhagen (KU), the University of California Davis (UCD), Aarhus University (AU, Denmark), the Geological Survey of Norway (NGU) and in continued collaboration with the Geophysical Laboratory, Carnegie Institution of Washington (USA) and the University of Oregon (USA).

Retrieval of Skaergaard intrusion drill cores (T.F.D.N., C.E.L., J.S., J.G.)

A total of 15 km of core from 27 drill sites (*c.* 80 tons) was recovered by Platinova A/S in 1989 and 1990. Apart from selected intersects transported to Canada for further investigation, the cores were stored in the open at the landing strip in Sødalen, 10 km east of the intrusion. Recognising the scientific value of the Skaergaard drillcores, SNF supported the crating and transport of 4.5 km of selected drillcore to Copenhagen, with the permission of Platinova A/S.

The Platinova A/S exploration license had expired by the end of 1999 and the cores were transferred to ownership of Greenland, represented by the BMP who supported and confirmed the agreement to save a representative proportion of the cores. Out of the total, five long cores for research purposes (*c.* 16 tons) and mineralisation intersects from all drill sites (*c.* 4 tons) were selected for storage at the Geological Museum, Copenhagen and the core library of the BMP. Cores were airlifted to Iceland for shipment to Denmark.

The research cores cover most of the Upper Zone of the intrusion (see Wager & Brown 1968) and extend into the upper part of the Middle Zone. The core material, new detailed *EG 2000* sample profiles from all the stratigraphy of the Layered Series not covered by the cores (Fig. 7), and core material and grab sample profiles returned from Platinova A/S storage in Canada,

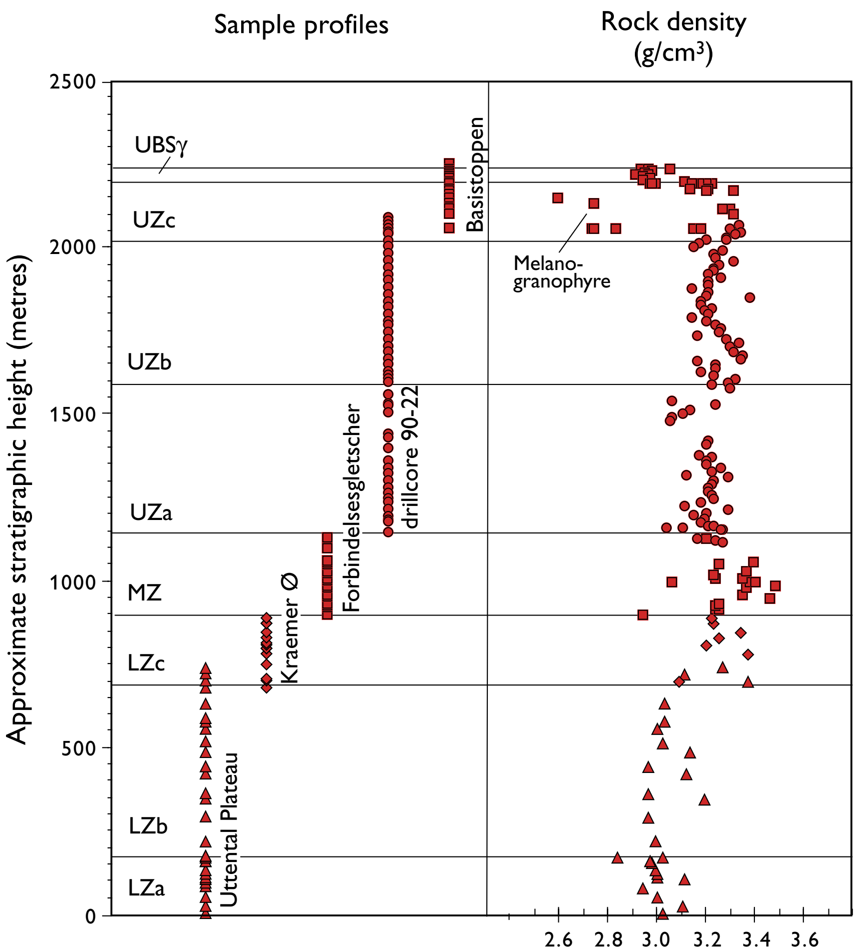


Fig. 7. **Left**: Stratigraphic coverage of the cumulus succession in the Skaergaard intrusion from LZa (Lower Zone a), through MZ (Middle Zone) and UZ (Upper Zone) to UBGγ (Upper Border Group gamma); see Wager & Brown (1968) for details of stratigraphy. Surface profiles: Uttental Plateau, Kraemer Ø, Forbindelsesgletscher and Basistoppen (all located within Skaergaard intrusion on Fig. 1). Drillcore DDH 90-22 is collared at point 312 on the north shore of Basisgletscher and covers the interval from upper MZ to middle UZc. The Skaergaard gold-palladium mineralisation is stratabound, located in the upper part of MZ and covered by the lower parts of DDH 90-22. **Right**: density profile through the stratigraphy. Modified from Nielsen *et al.* (2000).

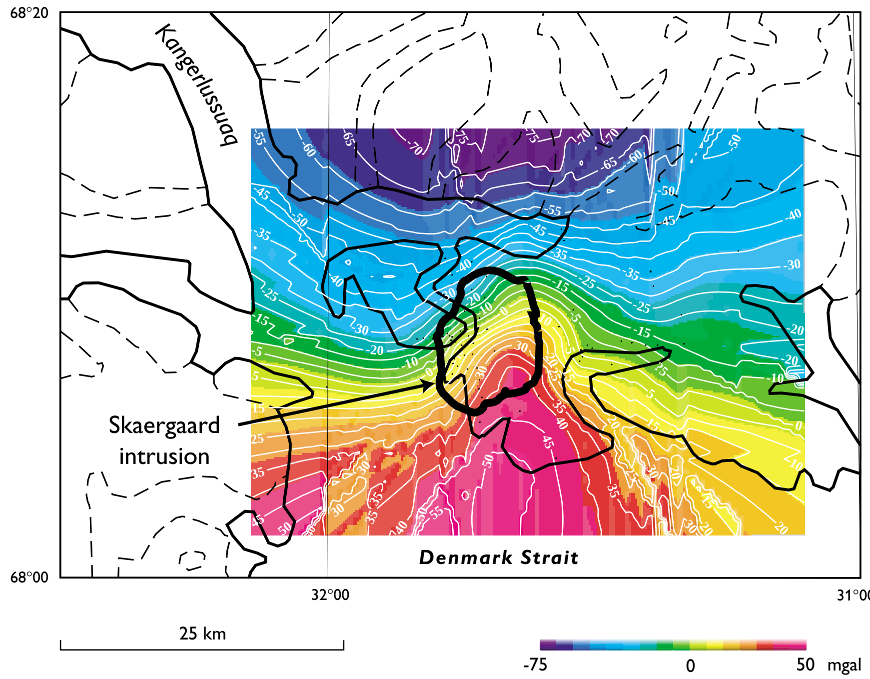
provide an unparalleled collection from the central part of the intrusion and form the basis for new Skaergaard research initiatives. These include structural modelling for mass balances for major elements and precious metals (Nielsen 2001), geophysical modelling based on gravimetry (see below), constraints on the line of liquid descent from melt inclusions, trace element studies on liquidus phases and a detailed record of modal, chemical and isotopic variations through the entire gabbro body (e.g. Tegner 1997; Nielsen *et al.* 2000) for refinement of numerical fractionation models.

Reconnaissance gravimetric survey of the Skaergaard intrusion (C.K.B., M.K.)

Pioneering gravimetric work on the Skaergaard intrusion carried out in the early 1970s was only published in abstract form (Blank & Gettings 1972, 1973). While knowledge of the regional field and the topographic effects was not available, these data have nevertheless formed the basis for numerous interpretations of the shape, depth and volume of the intrusion (e.g. McBirney 1975). The aim of the programme in summer 2000 was to determine whether new reconnaissance gravimetric data, corrected by software now available, would result in better constrained models for the shape and size of the intrusion and, in particular, better estimates of the dimensions of the hidden parts of the intrusion. The latter is a necessity for numerically constrained modelling of the development of the intrusion (see e.g. Wager & Brown 1968; McBirney 1975; Norton *et al.* 1984; Irvine 1992).

In 1986 Kort & Matrikelstyrelsen (KMS, the National Survey and Cadastre, Denmark) established a regional gravity survey of Greenland based on stations spaced approximately 25 km apart. In addition, KMS provided a digital map allowing for topographic corrections of the new gravimetric survey. Much of the new data was collected at sea level along the fjords, crossing the contacts of the intrusion by boat, using a LaCoste Romberg gravimeter (KU). A few stations were obtained with helicopter assistance in the high mountains over the central part of the intrusion.

Fig. 8. Bouguer anomaly map over the Skaergaard intrusion and surroundings based on *EG 2000* and KMS data. The intrusion is outlined in **heavy black line**, coast and glaciers in **thin black lines**. The effect from the regional field causes the negative gradient of the contour lines and the eastward displacement of the anomaly. Modified from Nielsen *et al.* (2000). For regional location, see Fig. 1.



The collected data were processed with help and software from KMS, and the Bouguer anomaly data are shown in Fig. 8. The preliminary results and models (not shown) identify a large anomaly over the Skaergaard intrusion and indicate that the intrusion continues to a depth of at least 3 km below sea level at its southern margin. This essentially agrees with models presented by Norton *et al.* (1984) and structural reconstructions (Nielsen *et al.* 2000; Nielsen 2001). The presence of two roots or feeders suggested by Norton *et al.* (1984) was not confirmed by the new data.

Late felsic magmatism and nodule-bearing lamprophyres

The Palaeogene magmatism along the coast of East Greenland is characterised not only by the voluminous flood basalts and contemporaneous gabbroic intrusions (e.g. the Skaergaard intrusion), but also by a large number of felsic and alkaline intrusions, intrusive complexes and alkaline dyke swarms (Fig. 1) emplaced over an extended period that lasted up to at least 20 Ma after the main period of flood basalt extrusion (Nielsen 1987).

Mineralisations are associated with many of these intrusions, including hydrothermal precious metals (Au, Ag), base metals (Pb, Zn) and molybdenum mineralisations. The Werner Bjerge complex (71°50′N; Fig. 1) contains a world class Mo deposit in a felsic pluton of the rifted East Greenland margin (Schønwandt 1988). Investigation of mineralisations at Amdrup Fjord (see Thomassen & Krebs 2001, this volume) and field work in the Kangerdlugssuaq intrusion in 2000 (see below) represent a coordinated effort aimed at the development of petrogenetic and mineralisation models for exploration strategies and a comprehensive description of the resource potential of the East Greenland rifted volcanic margin.

Kangerdlugssuaq alkaline intrusion: new comprehensive collections (C.K.B., D.W.P., M.S.R.)

Intrusive alkaline rocks outcrop over a large area in the Kangerlussuaq region (Brooks & Nielsen 1982b), but by far the largest contiguous body is the Kangerdlugssuaq alkaline intrusion (Kempe & Deer 1970; Kempe *et al.* 1970) and its satellites (Fig. 1). This intrusion is approximately circular with a diameter of about 33 km and covers an area of > 800 km^2, making it one of the world's largest syenitic bodies. Like many complexes of this type it contains both quartz-rich and feldspathoid-rich rocks, whose origin and mutual relationships are still under debate.

Apart from the work reported by Kempe & Deer (1970) and Kempe *et al.* (1970), very little detailed work has been undertaken on the Kangerdlugssuaq alkaline intrusion, largely due to its general inaccessibility. Wager (1965) discussed the general shape of the intrusion,

Fig. 9. Southern part of the Kangerdlugssuaq alkaline intrusion at the head of Amdrup Fjord. Telephoto view from helicopter, looking north-north-west. The summits reach > 1000 m.

Pankhurst *et al.* (1976) reported Sr- and O-isotopes, and Brooks & Gill (1982) presented analyses of the ferromagnesian minerals, together with a model for the intrusion's development.

The intrusion is largely covered by glaciers and outcrops consist of very steep-sided nunataks with frost-shattered, weathered material on the summits (Fig. 9). Fortunately, mass wastage along the glaciers provides ample amounts of fresh material, and altogether 120 samples from 42 separate localities were collected by helicopter from all parts of the intrusion.

Special attention was focused on the Astrophyllite Bay complex (Brooks & Nielsen 1982b; Nielsen & Brooks 1991), which is a mixed complex consisting of basic pillows in a syenitic matrix at the south-east margin of the intrusion. Nielsen & Brooks (1991) ascribed the origin of the syenites to *in situ* melting of the Precambrian host gneisses and chemical re-equilibration by diffusive processes. This hypothesis will now be tested in a Ph.D. project (Riishuus *et al.* 2001), using samples from precisely oriented slabs cut with a motor-driven diamond saw from the ice-polished roches moutonnées where the relationships between basic pillows, syenitic melt and basement gneiss are beautifully exposed (Fig. 10).

The Borgtinderne area (P.K., S.B.)

The Borgtinderne area along Kronborg Gletscher (Fig. 1) is an alpine glaciated terrain of extremely difficult access, and the area has only been briefly visited during reconnaissance expeditions. Kronborg Gletscher follows a N–S-trending lineament associated with abundant faulting and dyking, which separates two main structural blocks of flood basalts (Pedersen *et al.* 1997). Initial dating from the lineament shows post-plateau basalt igneous activity over *c.* 10 Ma between 50 and 40 Ma ago (C. Tegner, personal communication 2000).

The Borgtinderne syenite intrusion proved to be much more complex than described by Brown *et al.* (1978), with leucocratic syenite intruding an older, more mafic pluton of gabbro, diorite and pyroxenite. As observed in many other felsic intrusive complexes in East Greenland (Nielsen 1987), there is ample evidence for coexisting mafic and felsic magmas in pillowed dykes; these cut most lithologies in the Borgtinderne intrusion. A suite of plutonic rocks from the intrusion and samples of dykes cutting the syenites were collected for detailed studies and analyses.

A series of N–S-trending vertical lamprophyre dykes represent the youngest magmatic phase, and one of these dykes was found to carry small, but fresh, mantle xenoliths. These xenoliths appear to be finer grained than mantle xenoliths from basanitic dykes at Wiedemann Fjord, some 35 km further to the south (e.g. Bernstein *et al.* 1998).

A new ultramafic intrusion was located on the lower north-east slope of Ejnar Mikkelsen Fjeld. Seen from Borgtinderne the intrusion appears as an orange to yellow-brown weathering area of steep ridges. During two short helicopter visits the intrusion proved to be composed of dunite, with a few veins of pyroxenite and chromitite, which above 1900 m a.s.l. give way to pyroxenite. Whereas the plateau basalt host rocks are cut by a large number of mainly N–S-trending dykes, only two dykes were found to cut the ultramafic intrusives. The 'Ejnar Mikkelsen intrusion' – named after the massif in which it is found – shows similarities with the Lilloise intrusion (Brown 1973) situated 40 km to the south (Fig. 1).

The Borgtinderne syenites, the swarm of N–S-trending lamprophyre and basanite dykes, the nephelinite diatremes (Brooks & field parties 1996), the ultramafic 'Ejnar Mikkelsen intrusion' and the Lilloise intrusion all testify to the importance of the Kronborg Gletscher lineament as a major crustal structure that localised magmatism during a protracted period of *c.* 10 Ma after continental break-up along the coast of East Greenland.

Fig. 10. Basic pillows in syenite from the Astrophyllite Bay complex (located on north shore of Amdrup Fjord, Fig. 1). Slabs have been cut from crystalline basement (at bottom in foreground) and into the basaltic melt pillows at locations nearby for study of diffusion between felsic and basic melts. Hammer for scale. Colour version of figure from Brooks & Nielsen (1982b) and Nielsen (1987).

The NEAT seismic project (O.G., H.B.)

The aim of the *NEAT* (**N**orth-**E**ast **A**tlantic **T**omography) project is to use seismic surface waves crossing the North Atlantic Ocean to map the structure of the upper mantle beneath the region around the proposed Iceland hot spot. *NEAT* is a collaborative project between DLC and the University of Cambridge, UK. The project requires observations from a large number of permanent seismic observatories on both sides of the ocean as well as a number of temporarily deployed seismographs in the region. The latter were deployed at remote sites in East Greenland during *EG 2000*.

Temporary seismographs were deployed at Hjørnedal (70°21.1′N, 28°09.85′W), in Sødalen (68°12.20′N, 31°22.62′W), and in Kassortoq fjord (63°14.91′N, 42°02.09′W); all three sites are located at STOL air strips. Other temporary stations have been established at Danmarkshavn, Scoresbysund and Narsarsuaq (Fig. 1). These temporary stations supplement the three permanent observatories in Greenland operated by KMS.

Each of the remotely deployed stations consists of a Guralp 3T broadband seismograph, a RefTek acquisition system (16 bit, 4 Gbyte storage capacity), a large panel of solar cells (180 W), lead-acid batteries of 700 Ah capacity, and a windmill generator. All the equipment, apart from the solar cells and windmill generator, was placed in well-insulated boxes (20 cm thick insulation) and buried beneath a layer of sand bags. The sites will be visited annually for the next few years for data retrieval and maintenance.

Perspectives

The Palaeogene magmatic province in East Greenland represents the most voluminous and best exposed part of the onshore North Atlantic province. Since the earliest regional investigations in the 1930s (e.g. Wager 1934) the region has attracted international research activities. The participation of members of the international geological community in *EG 2000* confirms the continued interest as well as the educational potential of the Kangerlussuaq region (Table 1).

The logistic platform established by the grant from SNF for the retrieval of drillcores from the Skaergaard intrusion was used during *EG 2000* to carry out many and varied projects. The Sødalen base and air strip, the huts and the presence of fuel and depots, will facilitate continued field operations in the future and ensure access to the Kangerlussuaq region for both research and company interests.

With the completion of the DLC regional sampling programme in the flood basalts, the foundation has been laid for comprehensive modelling of the magmatism, plume involvement and the effects of crustal attenuation. The comprehensive sampling of the Skaergaard intrusion, the retrieval of drillcores for research purposes and gravimetric studies, provide opportunities for revival of studies of the structure and emplacement history of the Skaergaard intrusion and fundamental features of solidification and fractionation of basaltic magma in crustal magma chambers. The increasing focus on late mafic to felsic intrusions, and the finds of mantle nodules brought to the surface by the late magmatism, provide insights into, and open up opportunities for, studies of the complex interaction between mantle-derived magmas and the continental crust and the history of the underlying mantle during the plume-related continental break-up.

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Pre-basaltic sediments (Aptian–Paleocene) of the Kangerlussuaq Basin, southern East Greenland

Michael Larsen, Morten Bjerager, Tor Nedkvitne, Snorre Olaussen and Thomas Preuss

The recent licensing round in the deep-water areas south-east of the Faeroe Islands has emphasised the continued interest of the oil industry in the frontier areas of the North Atlantic volcanic margins. The search for hydrocarbons is at present focused on the Cretaceous–Paleocene succession with the Paleocene deep-water play as the most promising (Lamers & Carmichael 1999). The exploration and evaluation of possible plays are almost solely based on seismic interpretation and limited log and core data from wells in the area west of the Shetlands. The Kangerlussuaq Basin in southern East Greenland (Fig. 1) provides, however, important information on basin evolution prior to and during continental break-up that finally led to active sea-floor spreading in the northern North Atlantic. In addition, palaeogeographic reconstructions locate the southern East Greenland margin only 50–100 km north-west of the present-day Faeroe Islands (Skogseid *et al.* 2000), suggesting the possibility of sediment supply to the offshore basins before the onset of rifting and sea-floor spreading. In this region the Lower Cretaceous – Palaeogene sedimentary succession reaches almost 1 km in thickness and comprises sediments of the Kangerdlugssuaq Group and the siliciclastic lower part of the otherwise basaltic Blosseville Group (Fig. 2). Note that the Kangerdlugssuaq Group was defined when the fjord Kangerlussuaq was known as 'Kangerdlugssuaq'. Based on field work by the Geological Survey of Denmark and Greenland (GEUS) during summer 1995 (Larsen *et al.* 1996), the sedimentology, sequence stratigraphy and basin evolution of the Kangerlussuaq Basin were interpreted and compared with the deep-water offshore areas of the North Atlantic (Larsen *et al.* 1999a, b).

In August 2000, key stratigraphic sections were revisited by geologists from GEUS and Norsk Hydro and a number of additional localities described (Fig. 1). The aims of the field work included: (1) sedimentological description of Lower Cretaceous sandstones; (2) improved biostratigraphy in the Upper Cretaceous mudstone succession; and (3) detailed description of the transition between the uppermost sediments and the base of the volcanic succession. In addition, macrofossils (mostly ammonites, bivalves and belemnites) were sampled throughout the Cretaceous succession. Based on results from a preliminary diagenesis study (Larsen *et al.* 1999b), sandstones were collected across the contact metamorphic zone around Palaeogene intrusions in order to evaluate their thermal and diagenetic effects. The field work was financed with support from Norsk Hydro and formed part of a major field campaign in the Kangerlussuaq area (*EG 2000*) reported on by Nielsen *et al.* (2001, this volume).

Sedimentology

Lower Cretaceous (Christian IV Gletscher)

The oldest sediments in the Kangerlussuaq Basin are of Early Cretaceous (Aptian – Early Albian) age (Fig. 2). This succession is dominated by coarse-grained sandstones and was first described by Larsen *et al.* (1996, 1999a) from a locality north of Sødalen. At this locality a lower, alluvial succession is overlain by large-scale channelled and cross-bedded fluvio-estuarine sandstones (Larsen *et al.* 1999a). The general palaeocurrent direction was towards the east, but the lack of reference sections has hitherto hindered conclusions on distribution and palaeogeography. In summer 2000 a number of possible Lower Cretaceous reference sections were measured along the western side of Christian IV Gletscher (Fig. 1). These sections were briefly described during a helicopter reconnaissance visit in 1995, but more detailed measurements of sedimentological sections and sampling of ammonites was undertaken in 2000.

The sections are sandstone-dominated, and reach more than 170 m in thickness. The lowest parts are

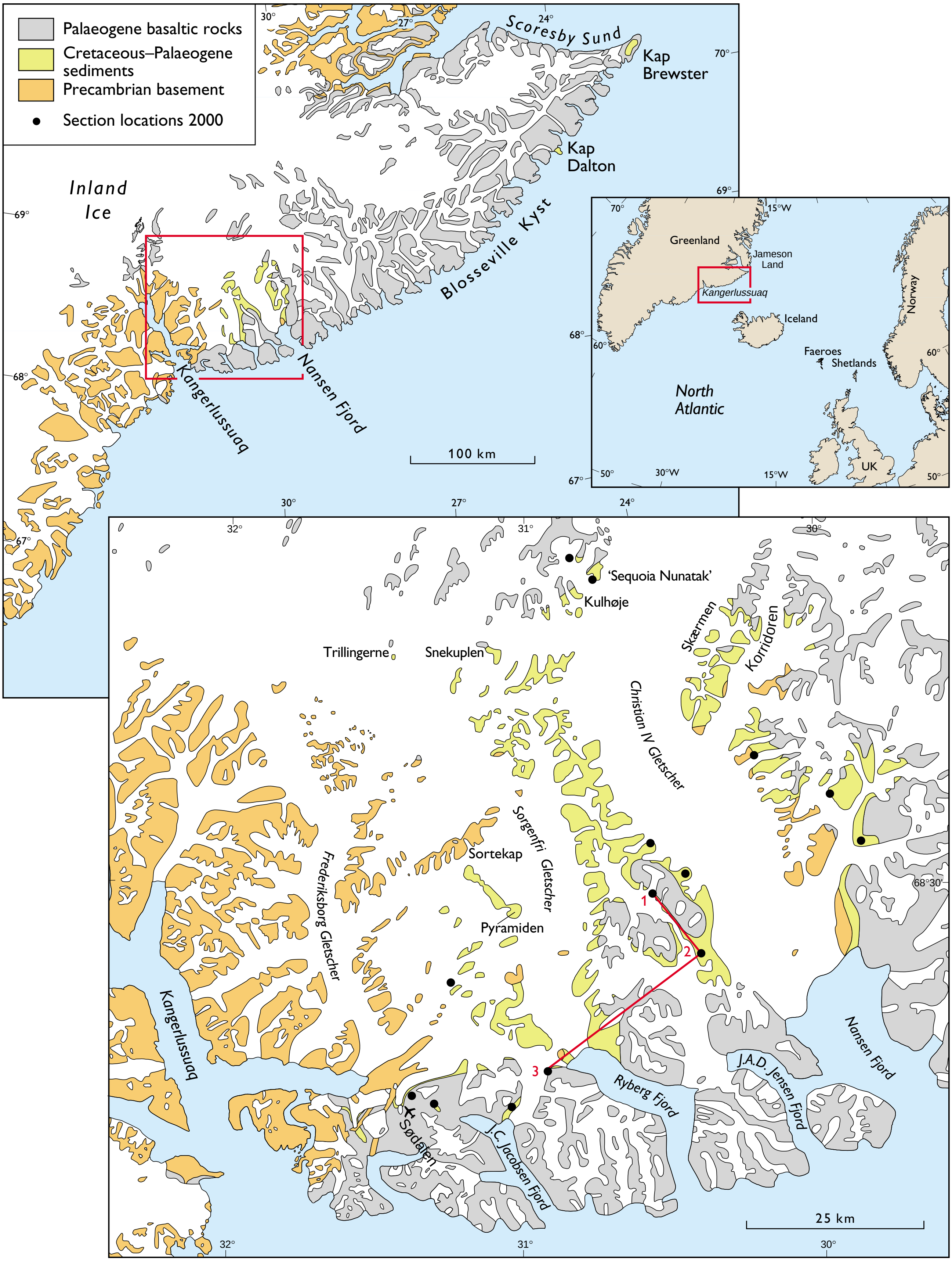

Fig. 1. Geological maps showing the distribution of Cretaceous–Palaeogene sediments and the Palaeogene flood basalts of the southern East Greenland volcanic province. The position of sections logged in 2000 (**black dots**) and localities mentioned in the text are indicated. **Red line** in lower map connects sections **1**, **2** and **3** shown in Fig. 5. Based on Larsen *et al.* (1996).

poorly exposed and consist of coarse-grained, locally pebbly, sandstones rich in coalified wood debris. These are overlain by medium- to coarse-grained, large-scale cross-bedded sandstones, which are bioturbated and show *Thalassinoides* isp. and *Planolites* isp. The upper boundary of the sandstone-dominated succession is a strongly carbonate-cemented horizon overlain by a thick succession of silty mudstones with numerous heteromorph ammonites. The Lower Cretaceous succession along the west side of Christian IV Gletscher is interpreted to consist of a lower alluvial part overlain by shallow marine deposits and finally offshore marine mudstones. The upwards change is thus the same as that seen in the Upper Aptian – Lower Albian succession at the locality north of Sødalen, and reflects an overall rise in sea level.

Upper Cretaceous – Paleocene ('Sequoia Nunatak')

Monotonous silty mudstones and fine-grained sandstones reaching several hundred metres in thickness (Fig. 3) dominate the Upper Cretaceous succession. The mudstones are best exposed in the area around Pyramiden and between Sorgenfri Gletscher and Christian IV Gletscher where they reach their maximum thickness. Nørgaard-Pedersen (1992) reported a probable Cretaceous succession at 'Sequoia Nunatak' (an unofficial name) north-east of Kulhøje, greatly expanding the then known extension of the Cretaceous basin (Fig. 1). The sediments were described as a few metres of fine-grained sandstones containing internal casts of echinoderms and ammonites. Field work in 2000, however, revealed in addition a several hundred metres thick succession of fine-grained micaceous sandstones just east of the locality described by Nørgaard-Pedersen. These sandstones contain a rich fauna of ammonites, echinoderms and bivalves of Late Cretaceous age. The fine-grained sandstones are truncated at the top of the succession by a 7 m thick conglomerate bed interpreted as a fluvial channel-fill, which is overlain by volcaniclastic deposits. The stratigraphic position of the conglomeratic unit immediately underlying the first volcanic deposits, together with the abrupt change from marine to continental deposits and the coarse-grained lithology, suggest that it may be correlated with the Schjelderup Member of the coastal areas (Soper *et al.* 1976). Biostratigraphic samples collected in 2000 may provide the evidence for the correlation between the nunatak area around 'Sequoia Nunatak' and the coastal region.

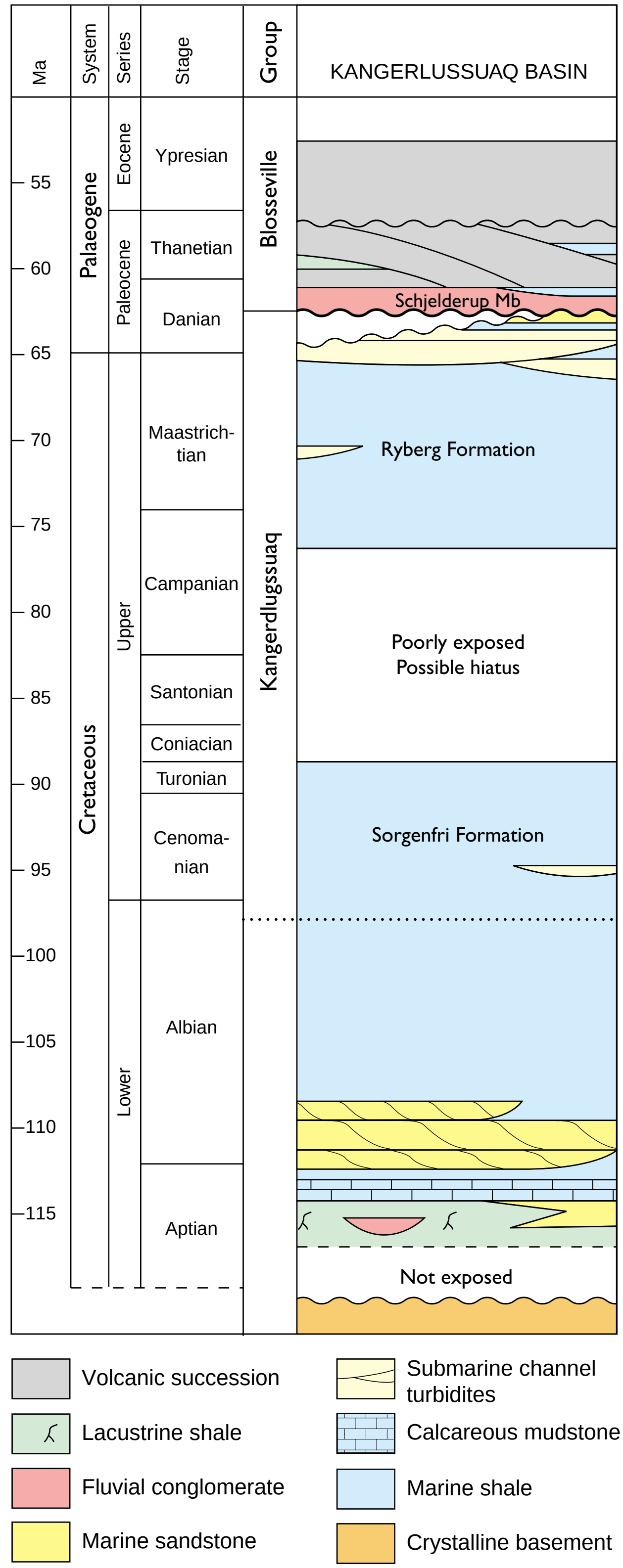

Fig. 2. Lithostratigraphy of the Kangerlussuaq Basin. The succession below the Sorgenfri Formation (Aptian – Early Albian) was not described until 1995 and therefore was not included in the lithostratigraphic scheme by Soper *et al.* (1976). A revision of this succession (below the dotted line) is in preparation by the senior author (M.L.). Based on Soper *et al.* (1976), Nielsen *et al.* (1981) and Larsen *et al.* (1999a).

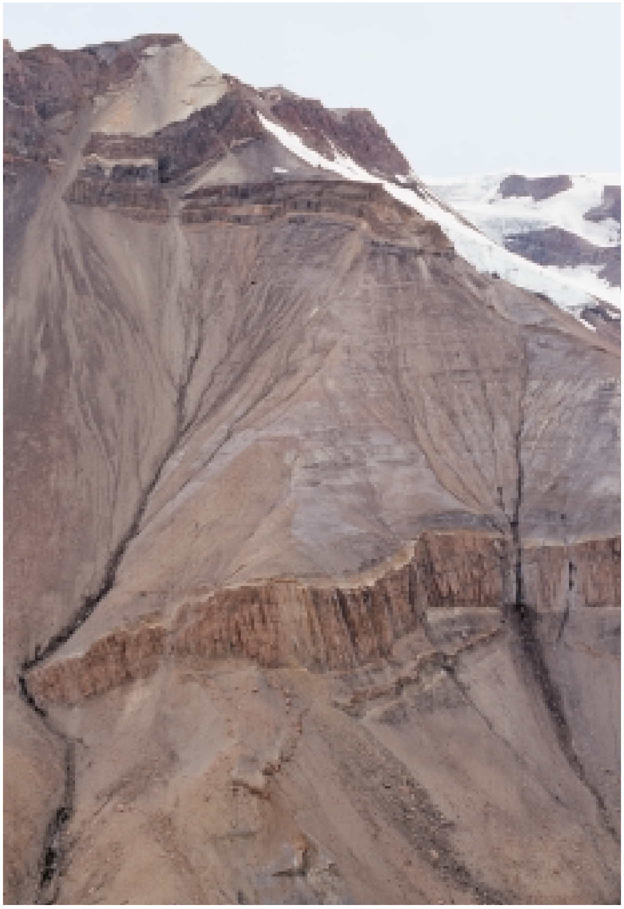

Fig. 3. Upper Cretaceous marine mudstone succession exposed along the western side of Christian IV Gletscher. The section shown is approximately 450 m thick and consists of silty, mica-rich mudstones with thin interbeds of fine-grained sandstones. Ammonites and echinoderms are present in several horizons and may form the basis for an improved Upper Cretaceous stratigraphy.

Paleocene (Ryberg Fjord)

The boundary between the Kangerdlugssuaq Group and Blosseville Group is represented by a major unconformity which separates Upper Cretaceous or Lower Paleocene marine mudstones below from coarse-grained fluvial deposits above (Soper *et al.* 1976; Dam *et al.* 1998; Larsen *et al.* 1999a). However, towards the coast (localities 2 and 3, Ryberg Fjord; Fig. 1) the unconformity correlates with a number of less distinct bounding surfaces separating shallow marine, deltaic and fluvial units. At Ryberg Fjord, a thick sandstone-dominated succession is exposed (Fig. 4). It consists of marine, fossiliferous fine-grained sandstone unconformably overlain by an up to 7 m thick pebbly sandstone bed, in turn overlain by black carbonaceous mudstones and fine-grained sandstones showing rootlets (Fig. 5). The erosionally based pebbly sandstone is interpreted as a fluvial channel-fill that marks a change from marine to dominantly continental deposition. Higher in the succession a return to shallow marine conditions is marked by strongly bioturbated sandstones interpreted as upper shoreface and beach deposits. The siliciclastic succession is overlain by a thick succession of volcaniclastic deposits and hyaloclastites. The Paleocene succession at Ryberg Fjord comprising shallow marine and deltaic deposits is thicker and more complete than that described from the inland areas. This indicates that increasing accommodation room was present in the more basinal areas to the south-east and that multiple episodes of shoreface and delta progradation took place during the uplift phase preceding the onset of volcanism in East Greenland.

Fig. 4. Paleocene sandstones exposed at Ryberg Fjord. The sandstone unit in the foreground is 7 m thick and is interpreted as a fluvial channel-fill. These coarse-grained channel sandstones were deposited following regional uplift in the mid-Paleocene, just before the onset of volcanism. In the background volcaniclastic deposits and hyaloclastites can be seen.

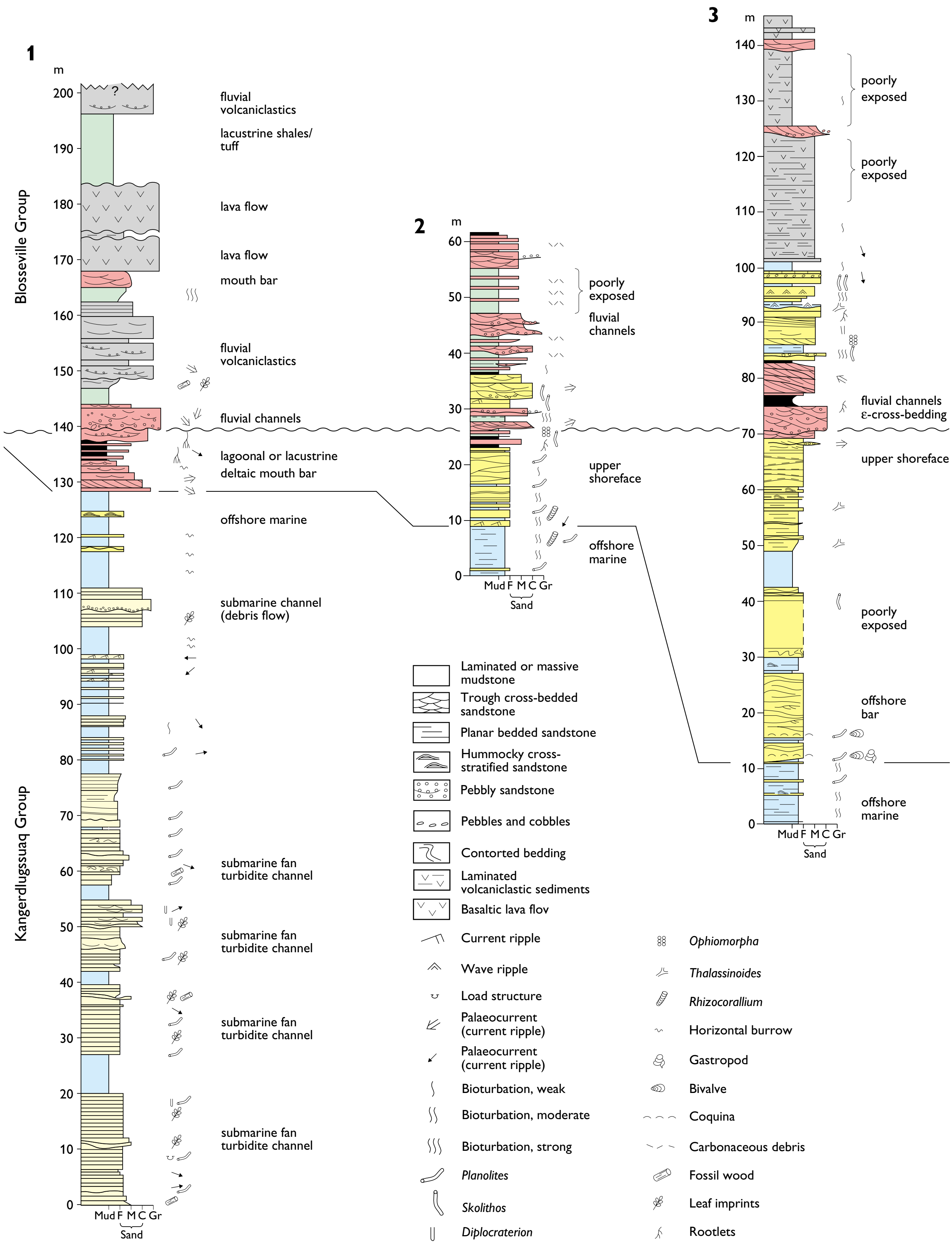

Fig. 5. Geological logs showing correlation of the Paleocene successions in the central part of the Kangerlussuaq Basin. Locations of sections (**1**, **2**, **3**) are shown on Fig. 1. Note the thick shallow marine and deltaic succession present below the unconformity in the southernmost section (**3**) compared to the strong truncation that occurs inland. The succession indicates that repeated progradation of shallow marine and deltaic successions occurred during the mid-Paleocene pre-volcanic uplift. **Colour coding** refers to depositional environments. For legend, see Fig. 2.

Stratigraphy

Biostratigraphy

Detailed understanding of the Kangerlussuaq Basin has hitherto been hampered by the low resolution of the biostratigraphic data. This is partly a consequence of failure to collect macrofossils, and partly due to very low yields of microfossils from the existing sample material. In order to overcome these problems special attention was paid to the collection of macrofossils, and several mudstone sections situated away from major intrusions were sampled for palynological work (Fig. 3). The efforts put into the macrofossil collecting were rewarded, such that close to 50 ammonites representing both Lower and Upper Cretaceous species were brought back from the field.

Lithostratigraphy

The discovery of an Aptian–Albian, sandstone-dominated succession below the Sorgenfri Formation in 1995 (Fig. 2) and the finds of new ammonite-bearing intervals made it clear that a revision of the existing lithostratigraphy was necessary (Larsen *et al.* 1999a). However, the lack of biostratigraphic control in the Upper Cretaceous mudstone-dominated succession, and the poor understanding of the lower volcanic succession which appeared to interfinger with the sedimentary rocks, impeded interpretation. The results of the field work in 2000 combined with biostratigraphical and sedimentological data compiled by Cambridge Arctic Shelf Programme (CASP) will enable a common lithostratigraphic scheme for the Kangerlussuaq Basin to be published in the near future. This new lithostratigraphy is a collaborative project between GEUS and CASP.

Diagenesis

The sandstones of the Kangerlussuaq Basin have been strongly diagenetically altered, due to their position close to major Palaeogene intrusive centres and a burial history that included rapid pre-volcanic uplift followed by deep burial beneath continental flood basalts. The complex diagenetic history comprises chlorite and illite precipitation, mechanical crushing, detrital feldspar dissolution and albitisation followed by albite precipitation and quartz overgrowth. The last common phase is calcite, while later kaolinite is only observed in the coarse-grained fluvial sandstones of the Schjelderup Member (Larsen *et al.* 1999b). The original excellent porosity of the sandstones is only preserved in a few places due to early chlorite coating of grains preventing quartz overgrowth. Otherwise, the original porosity has been completely destroyed, and the present porosity (5–10%) mainly reflects secondary porosity originating from dissolution of detrital feldspar. The dissolution process seems to be significantly enhanced in the coarse-grained sandstones in areas with many intrusions. The secondary pore space may be reduced by authigene albite growth on detrital grain remnants together with later syntaxial quartz overgrowths engulfing the albite (Fig. 6). In places, clay coatings or ductile clay clasts can be seen to inhibit quartz ingrowths, thus preserving the secondary porosity. The coarse-

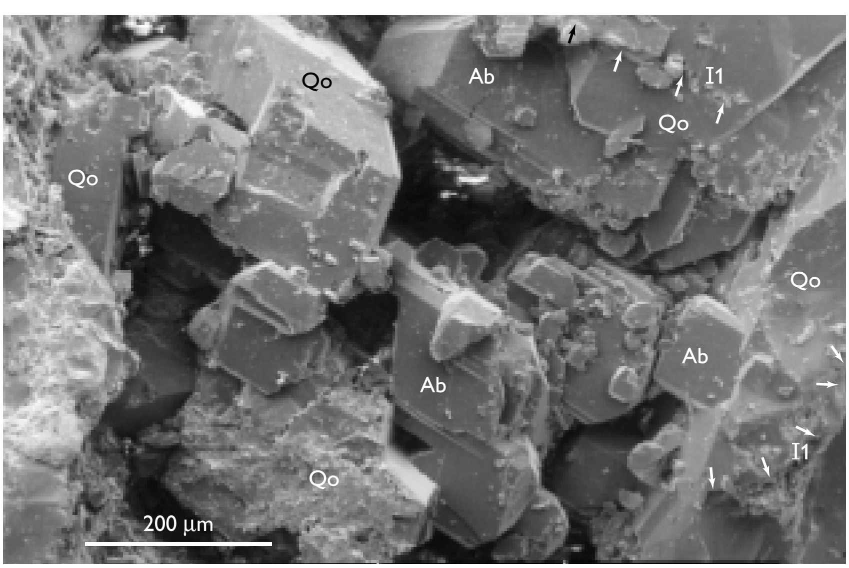

Fig. 6. Scanning electron photomicrograph of a coarse-grained Paleocene sandstone, showing secondary pore space formed by feldspar dissolution. The pore space is partly filled by growth of euhedral albite crystals (**Ab**) nucleated on the detrital feldspar remnants. Illitic clay lining (**Il**) marks the boundaries of the former detrital grains (**arrows**). Later, euhedral quartz (**Qo**) overgrows the clay linings and engulfs the authigene albite.

grained sandstones in the north-eastern part of the basin show the most complete feldspar dissolution, but also experienced the most intensive phase of late quartz overgrowth, which nearly infilled all of the secondary formed porosity.

In order to better understand the diagenetic history and evaluate models for sandstone diagenesis in sub-basaltic settings, sandstone samples from the measured sections were studied. However, local effects from cross-cutting basic dykes and sills have strongly influenced diagenesis, and thus sandstones were collected across the contact metamorphic zone from adjacent to the intrusion to a distance as far away as two to three times the thickness of the intrusion. The results of these investigations will be compared with the samples unaffected by intrusions in order to separate local and regional effects.

Conclusions

Field work in the Kangerlussuaq Basin in 2000 has added much information to the understanding of the basin evolution. Most important, perhaps, is the improved biostratigraphic resolution that allows identification and correlation of unconformities between measured sections. Unconformities mark major changes in basin configuration and are often associated with uplift and erosion. The unconformity present at the base of the Schjelderup Member, and now recognised throughout the basin, thus suggests that coarse-grained sediments bypassed the Kangerlussuaq area at this time and were transported across the East Greenland margin to offshore basins to the south-east. With a pre-drift position only 50–100 km north-west of prospective areas around the Faeroe Islands the understanding of the pre-basaltic basin evolution in southern East Greenland may be used to identify possible reservoir intervals and play types in the undrilled deep-water areas of the northern North Atlantic volcanic margins.

Future work

The Palaeogene flood basalts along the Blosseville Kyst are part of an extensive basalt province extending from Kangerlussuaq in the south to Scoresby Sund in the north. Sediments are exposed only at two isolated localities along the coastal stretch, at Kap Dalton and Kap Brewster (Fig. 1). These two localities form important datapoints for reconstruction of the North Atlantic region during continental break-up and for biostratigraphic control of the onset and duration of the volcanism in southern East Greenland. Both localities were visited by geologists in the 1970s (Birkenmajer 1972; Soper *et al.* 1976), but no recent sedimentological descriptions have been published. In the summer of 2001 field work will be carried out in the sedimentary successions at Kap Brewster and Kap Dalton using sedimentological, biostratigraphical and sequence stratigraphical methods. The results will be integrated with basin models and stratigraphy in the areas to the south-west around Kangerlussuaq and to the north in North-East Greenland.

Acknowledgements

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Vendian – Lower Ordovician stratigraphy of Ella Ø, North-East Greenland: new investigations

Svend Stouge, Douglas W. Boyce, Jørgen Christiansen, David A.T. Harper and Ian Knight

Field work on Ella Ø in summer 2000 formed part of an ongoing research project to investigate the development of the Laurentian margin facing the Iapetus Ocean in the early Palaeozoic (Fig. 1). The extensive study region includes the well-exposed strata extending along the present coastlines of western Newfoundland, Canada, North-West Ireland and North-West Scotland, North-East Greenland and Svalbard. It is hoped to establish both the architectural and chronostratigraphic continuity and variation of these now disparate parts of a once contiguous platform.

Detailed lithostratigraphic studies of the uppermost Neoproterozoic (Vendian) – Lower Palaeozoic succession of North-East Greenland will provide the framework to underpin sedimentological and palaeogeographic interpretations as well as assist with diagenetic and detailed biostratigraphic studies. Geochemical data from isotopic analyses will support these studies. Detailed collection of macrofaunas (including trilobites, brachiopods and gastropods) and microfaunas (conodonts) should improve chronostratigraphic understanding.

The 2000 results suggest that the existing lithostratigraphy will require revision. For example, studies of measured sections show that dolomitisation in much of the Cambrian carbonate succession has overprinted and obscured lithostratigraphic boundaries.

Ella Ø study area

Vendian and Cambro-Ordovician sediments are exposed in a broad N–S-trending belt of the fjord region of North-East Greenland between latitudes 71°38′N and 74°25′N (Fig. 2). On Ella Ø the Vendian Tillite Group overlies

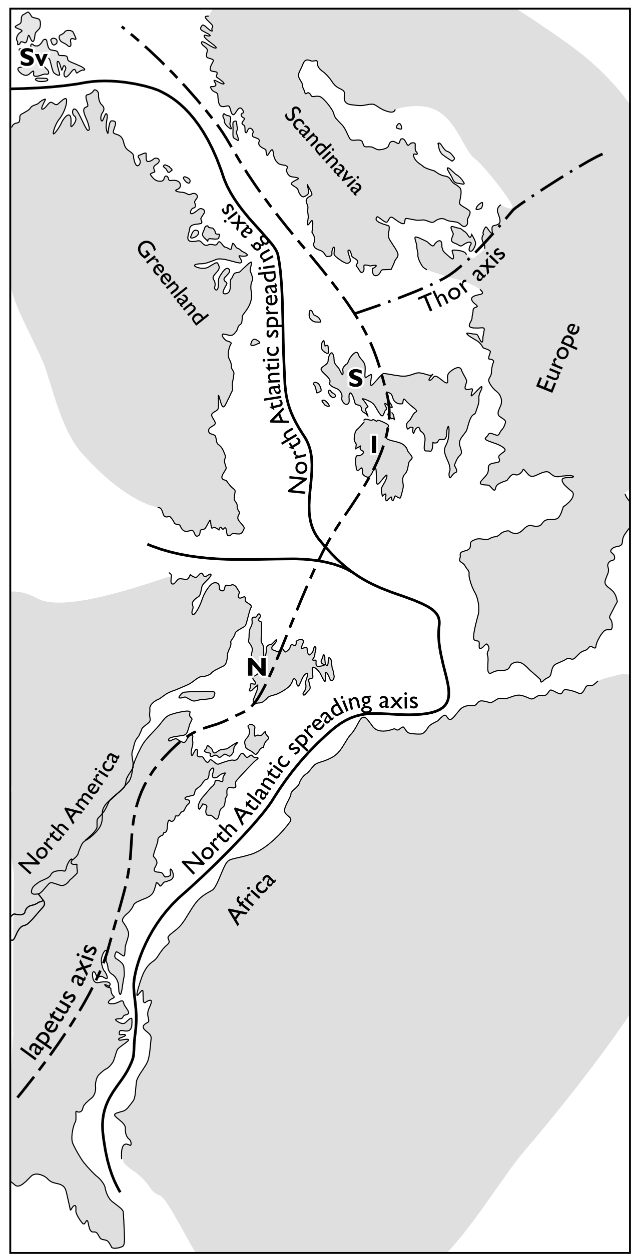

Fig. 1. Spreading axis of the North Atlantic Ocean compared with the position of the Early Palaeozoic Iapetus suture. Svalbard (**Sv**), Western Newfoundland (**N**), North-West Ireland (**I**), North-West Scotland (**S**) and Greenland are on the same side of the Iapetus axis. Modified from Williams (1987) and Berthelsen (1998).

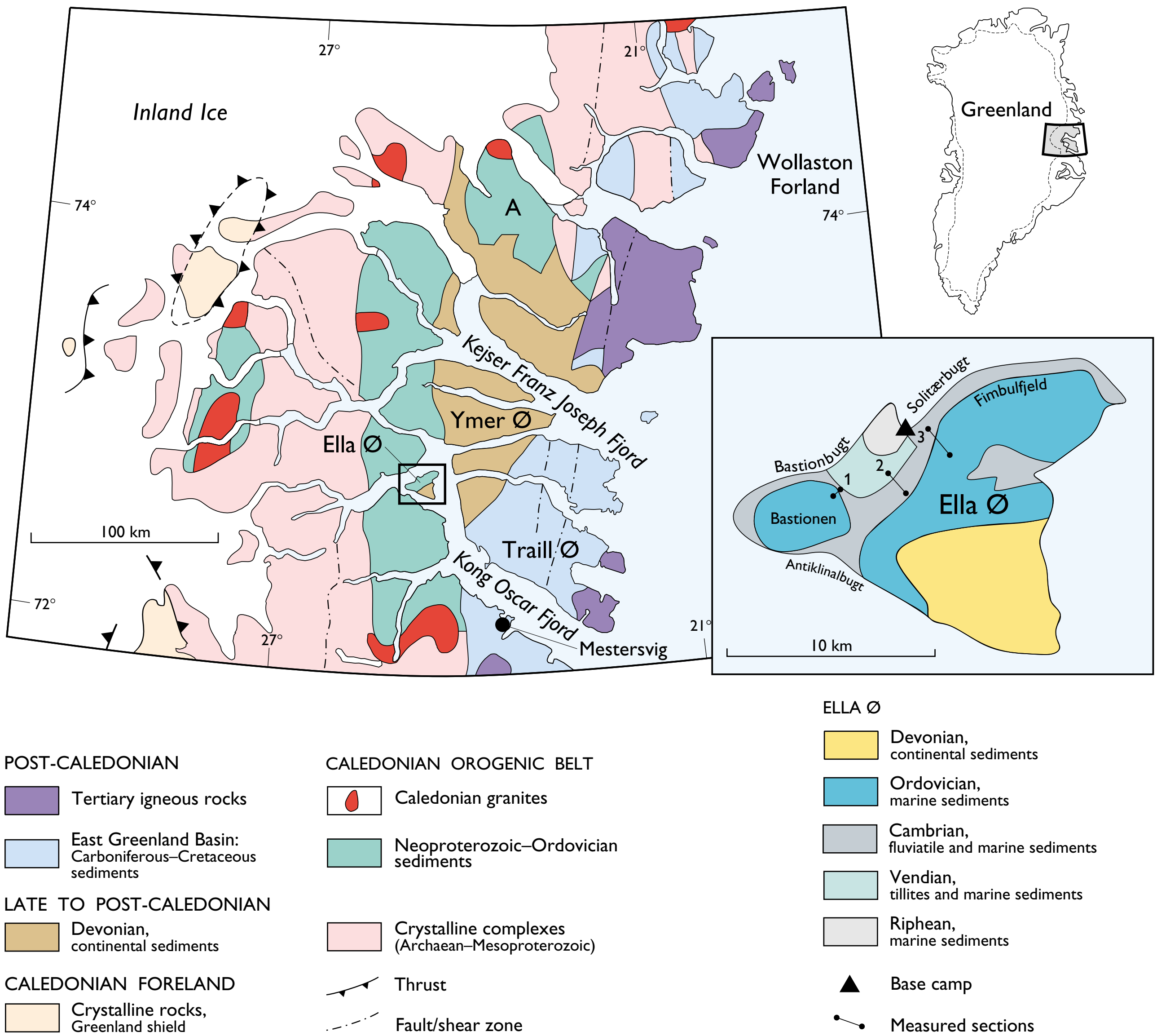

Fig. 2. Locality map of southern North-East Greenland with simplified geology. **A**: Albert Heim Bjerge. The map of Ella Ø shows locations of the base camp (see Fig. 3) and the investigated sections. Geology modified from Poulsen & Rasmussen (1951), Cowie & Adams (1957) and Henriksen (1994).

the Riphean Eleonore Bay Supergroup, while the Cambro-Ordovician succession is unconformably overlain by Devonian rocks. The pre-Devonian sediments are deformed by major Caledonian folds, the Bastion syncline and Kap Oswald anticline of Cowie & Adams (1957), associated with minor thrust and normal faults. A strong ridge-and-valley topography essentially reflects rock lithologies and structure with valleys associated with recessive units or minor low-angle faults. The highest elevation is Bastionen at 1367 m (Figs 2, 5).

Field work was carried out from the scientific station at Solitærbugt established by Lauge Koch in 1931 (Fig. 3), and focused on three sections exposed to the east, south and west (Fig. 2). The field party consisted of the five authors, responsible for stratigraphy, geochemistry, palaeontology and sedimentology. This report provides preliminary results, with field identifications of macrofossils, and documents well-developed microbialites (*sensu* Riding 1991) in the Ordovician sequence.

Vendian

Tillite Group

The Vendian System in North-East Greenland is represented by the 800 m thick Tillite Group (Hambrey & Spencer 1987; Hambrey 1989; Herrington & Fairchild

Fig. 3. The scientific station on Ella Ø used as base camp for the summer 2000 field work (see Fig. 2 for location). The outcrops behind the house are carbonates of the Riphean Eleonore Bay Supergroup, which also make up the mountains in the background.

1989), which overlies disconformably the Eleonore Bay Supergroup (Sønderholm & Tirsgaard 1993; Tirsgaard & Sønderholm 1997). Of the five formations (Fig. 4), the upper Spiral Creek Formation was studied in detail.

Spiral Creek Formation

The Spiral Creek Formation, 25–55 m thick, comprises varicoloured siltstones interbedded with sandstones. The depositional environment is interpreted as evaporitic non-marine (Fairchild 1989; Fairchild & Herrington 1989).

The uppermost member of the formation – 'unit e' of Cowie & Adams (1957) – is known only from Ella Ø, where it is well exposed in section 2 and in Antiklinalbugt (Fig. 2). It comprises 7–14 m of yellow-weathering, fine-grained dolostones associated with black chert developed along bedding surfaces or as irregular lenses. A quartzitic conglomerate with rounded chert clasts occurs at the base, overlying a disconformity. Black dense dolomites are considered indicative of anoxic bottom conditions in a lagoonal setting. No fossils have been recorded, but a latest Proterozoic age can be presumed.

Cambro-Ordovician

The Lower Cambrian shelf succession on Ella Ø starts with dominantly clastic to mixed clastic-carbonates of the Kløftelv, Bastion and Ella Island Formations (Fig. 4). These units, investigated at sections 1 and 2, record part of a transgressive–regressive sequence that also includes part of the overlying Cambrian to Lower Ordovician carbonate succession (Hyolithus Creek, Dolomite Point, Antiklinalbugt, Cape Weber and Narwhale Sound Formations; Fig. 4). Our observations ranged from the Kløftelv Formation to the Antiklinalbugt Formation. The Cape Weber and Narwhale Sound Formations were not studied in detail, while the uppermost unit in the succession (Heimbjerge Formation) is

SYSTEM	GROUP	FORMATION
Ordovician		Heimbjerge Narwhale Sound Cape Weber Antiklinalbugt
Cambrian		Dolomite Point Hyolithus Creek Ella Island Bastion Kløftelv
Vendian	Tillite	Spiral Creek Canyon Storeelv Arena Ulvesø

Fig. 4. Stratigraphic nomenclature of the Vendian – Middle Ordovician sediments of North-East Greenland. **Dashed line** indicates that the exact location of the Cambrian–Ordovician boundary is poorly constrained.

Fig. 5. Bastionen seen from the north; the nearest peaks left of centre are 1200 m above the terrain in the foreground. The dark-grey and yellow sediments at left form the Canyon Formation (**C**), which is overlain by yellow dolostones of the Spiral Creek Formation (**SC**). Reddish-coloured sediments are sandstones of the Kløftelv Formation (**K**), and the dark-green to grey recessive unit is the Bastion Formation (**B**). The succeeding thick-bedded rocks forming the steep cliffs of Bastionen are Cambrian and Lower Ordovician carbonates (**C–O**).

not preserved on Ella Ø. The Cambro-Ordovician sequence is more than 2000 m thick (Cowie & Adams 1957; Smith 1991; Smith & Bjerreskov 1994).

Kløftelv Formation

The Kløftelv Formation was measured in section 2 to be 70–75 m thick, and disconformably overlies 'unit e' of the Spiral Creek Formation. The base of the formation is an erosional surface; an irregularly bedded, pebbly quartz arenite with rounded shale pebbles is succeeded by a vivid-red unit of interbedded shale and cross-bedded and cross-laminated, very fine to fine-grained quartz arenite.

The Kløftelv Formation is dominated by fine- to medium-grained, white to pale-pink and red quartz arenite, arranged in metre to decametre-scale sequences. Wedge-shaped trough cross-beds dominate. Herringbone cross-stratification is common and locally foresets are overturned below scours. Rare sinuous ripple-marks occur. Poor exposures precluded detailed palaeocurrent measurements, but those made suggest polymodal directions dominated by a southward flow, with subordinate flow directions to the north-east.

The formation was probably laid down in a relatively high-energy, near shore to sandy shoreline setting. Trace fossils were noted by Hambrey & Spencer (1987), and an early Cambrian age is considered likely (Vidal 1979, fig. 4; Pickerill & Peel 1990, fig. 1).

Bastion Formation

The Bastion Formation, *c.* 140 m thick, is composed of glauconitic siltstone, shale, minor sandstone and calcareous sandstone. The formation crops out at high altitudes in the steep cliffs at Bastionbugt (Figs 2, 5) where the lower boundary is well exposed, and along the nearly vertical wall of Antiklinalbugt; at Solitærbugt minor exposures are easily accessible. Lower Cambrian fossils are common in the lower and middle parts of the formation (see e.g. Poulsen 1930; Cowie & Adams 1957; Cowie & Spencer 1970; Pickerill & Peel 1990).

Ella Island Formation

This formation is 80 to 100 m thick (Cowie & Adams 1957). In the lower part thin beds of laminated siltstone, commonly with trace fossils, are intercalated with shale at the base of metre-scale sequences, generally capped by a thick unit of medium-bedded calcareous siltstone and silty limestone. A few palaeocurrent measurements indicate south-eastward flow.

The upper part of the formation is made up of thin-bedded lime mudstone in 1–3 m thick sequences; these are intercalated with 20–70 cm thick beds of intraclastic skeletal grainstone, pebbly grainstone and rudstone. Vertical U-shaped or tubular burrows occur. The grainstone beds are rich in locally derived angular platy clasts of limestone (up to 10 cm) and locally dolostone.

Salterella and trilobites such as *Olenellus* and *Wanneria* are common in some beds (Poulsen 1932) indicating the *Bonnia-Olenellus* zone, i.e. late Early Cambrian.

Hyolithus Creek Formation

The dolostones of the Hyolithus Creek Formation are 145 m thick at Fimbulfjeld; at Antiklinalbugt the formation was measured at 210 m by Cowie & Adams (1957).

Patches and beds of pale grey, very fine-grained limestone remain as vestiges in both the mound and laminated facies at the base of the dark dolostones forming the upper 48 m interval of the formation. This limestone-bearing interval appears to correlate with limestones noted by Cowie & Adams (1957) about 100 m above the base of the dolostone at both Antiklinalbugt and in Albert Heim Bjerge suggesting that this may be a useful marker unit.

The dolostones of the Hyolithus Creek Formation are barren of fossils but *Salterella* in the limestone-bearing interval suggests the *Bonnia-Olenellus* Zone.

Boundary between the Ella Island and Hyolithus Creek Formations

From a conformable section in the east limb of the Kap Oswald anticline along the south-facing cliff wall at Antiklinalbugt, Cowie & Adams (1957) described the Ella Island Formation as comprising lower and upper limestone units separated by shale, and the Hyolithus Creek Formation as dark dolomite with minor limestone. Our logging on the same fold limb at sections 2 and 3 (Fig. 2) on the west slopes of Fimbulfjeld indicates that Cowie & Adams' (1957) boundary is a nearly stratiform dolomitisation front. A more natural boundary would be at the base of an underlying package of ribbon limestone and thinly bedded and bioturbated limestone. These rocks are replaced upwards by the dolostones that define the Hyolithus Creek Formation of Cowie & Adams (1957). If parts or all of the upper limestone of Cowie & Adams (1957) are incorporated in the Hyolithus Creek Formation, the revised Ella Island Formation would be no more than 60 m thick on Ella Ø. Further work will be necessary to confirm this.

Dolomite Point Formation

The Dolomite Point Formation is 260 m thick at section 3 on Fimbulfjeld (Fig. 2); Cowie & Adams (1957) recorded 330 m at Antiklinalbugt. It consists of grey microcrystalline dolostones, argillaceous dolostones and pale-grey and green-grey shale intercalated with two decimetre thick intervals of dark-grey sucrosic dolostone.

The base of the formation is at the first continuous interval of light-grey, thin-bedded microcrystalline dolostone above the Hyolithus Creek Formation. The contact is not well exposed at section 3, but appears to be sharp and conformable. The topmost 20 m included by Cowie & Adams (1957) in the Dolomite Point Formation should probably be assigned to the overlying Antiklinalbugt Formation; this interval consists of sucrosic dolostones similar to the basal limestones of the Antiklinalbugt Formation.

Six members are provisionally recognised, and will be described elsewhere. No body fossils are known, but burrow-mottling and thin tubular burrows (possibly *Planolites*) occur sporadically. The formation is younger than the uppermost Lower Cambrian Hyolithus Creek Formation and older than the lowermost Ordovician Antiklinalbugt Formation.

Antiklinalbugt Formation

The Antiklinalbugt Formation was introduced by Peel & Cowie (1979) to replace the Cass Fjord Formation of North-East Greenland as used by Poulsen (1930), Poulsen & Rasmussen (1951) and Cowie & Adams (1957). The Cass Fjord Formation is now restricted to north-western Greenland (Henriksen & Peel 1976) and adjacent Canada (De Freitas & Mayr 1995).

The Antiklinalbugt Formation, 235 m thick, consists of muddy, bioturbated carbonates of peritidal to subtidal aspect, and siltstones to shale interbedded with subtidal limestones. Planar to domal stromatolitic and thrombolite mounds become larger and more complex up-section. The carbonate sediments vary from dolostone to selectively dolomitised limestone to almost pure limestone. Three members are recognised (Cowie & Adams 1957).

The microbial buildups (*sensu* Kennard & James 1986; see Riding 1991) are composed of stromatolitic-thrombolite-?sponges and cryptic microbialites. The mounds range from single colonies to well-defined microbial constructions (Fig. 6), whose development appears to be associated with the progression of the basal lower Ordovician transgression. The succession culminates with prominent and complex thrombolitic-stromatolitic-?sponge microbial mounds (Fig. 7).

The gastropod *Sinuopea whittardi*? Poulsen is the earliest fossil recovered; brachiopods and trilobites occur

Fig. 6. Vertical cross-section of well-developed microbial mounds in the upper part of the lower member of the Ordovician Antiklinalbugt Formation. The mounds, 1.7 m high, are composed of thrombolites, stromatolites and minor lithid sponges, with grainstones between each buildup. The recessive middle member of the formation is seen in the upper part of the photograph. Section 3 on Fimbulfjeld; hammer (centre) is 28 cm long.

Fig. 7. The upper surface of the microbial mound in Fig. 6, showing the oval to rounded shape of the thrombolites.

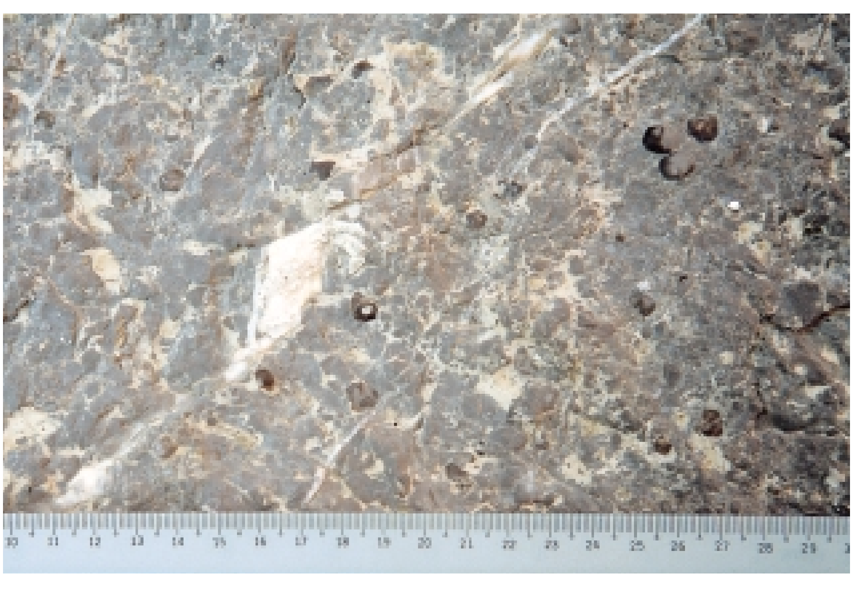

Fig. 8. Clusters of disarticulated shells of a finklenburgiid orthide brachiopod on an upper bedding surface from the middle member of the Antiklinalbugt Formation (section 3).

in the upper part of the lower member. Trilobites and brachiopods, and occasionally orthide brachiopods (Fig. 8), occur in the middle member; Poulsen (1930) reported graptolites.

Hystricurus armatus Poulsen and species of *Symphysurina* dominate the trilobite fauna. The presence of ?*Mannschreekia* sp., *Symphysurina woosteri* Ulrich, *Bellefontia* sp. and *Clelandia* sp. indicate the Antiklinalbugt Formation is Early Canadian (Gasconadian) *Symphysurina* and *Bellefontia-Xenopstegium* zones (Lower Ordovician).

The new fossil collections suggest that the boundary with the overlying Cape Weber Formation is a substantial hiatus; the basal beds of the latter formation contain ?*Cyptendoceras* sp. undet. indicating a Late Canadian (Jeffersonian) age. The lack of Middle Canadian macro-taxa (e.g. *Diaphelasma*, *Bassleroceras*, *Lecanospira* or *Hillyardina*) indicates a condensed sequence or major hiatus, a view in accordance with Poulsen (1930) and Poulsen & Rasmussen (1951), who suggested that much of the Lower Canadian and all of the Middle Canadian are not represented on Ella Ø.

Summary

The 2000 field work allows for the following interpretations.

1. An erosional surface developed at the top of 'unit e' of the Spiral Creek Formation on Ella Ø is overlain by the Kløftelv Formation. Northwards the former formation wedges out and the Kløftelv Formation rests on the Canyon Formation (Hambrey & Spencer 1987; Hambrey *et al.* 1989). This is indicative of a regional hiatus or disconformity at the base of the Kløftelv Formation, which conventionally is taken to be the base of the Cambrian in North-East Greenland.

2. The Lower Cambrian Ella Island and Hyolithus Creek Formations comprise a shallowing-upward sequence of fine-grained siliciclastics and limestones conformably above the shales of the Bastion Formation. The present contact between the Ella Island and Hyolithus Creek Formations is conformable and coincides with a dolomitisation front; the upper limestones of the Ella Island Formation (*sensu* Cowie & Adams 1957) would be better placed in a revised Hyolithus Creek Formation. The successions separated by such a boundary would be predominantly siliciclastic below and carbonate above.

3. The microbialite developments in the Antiklinalbugt Formation are characteristic for the Upper Cambrian to Lower Ordovician interval along the margins of Laurentia (Kennard & James 1986; Knight & James 1988; De Freitas & Mayr 1995). Microbial mounds and buildups similar to those in the Antiklinalbugt Formation are also reported from time-equivalent beds, e.g. the Cape Clay Formation of north-western Greenland (Dawes *et al.* 2000) and Arctic Canada (De Freitas & Mayr 1995).

4. The prominent hiatus recorded between the Antiklinalbugt and Cape Weber Formations corresponds to the Demingian Stage of the Canadian Series. An equivalent but less extensive hiatus is known elsewhere along the Iapetus margin in North America (Boyce 1989; James *et al.* 1989; Boyce & Stouge 1997) and is associated with an important faunal extinction event (Ji & Barnes 1993).

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Periglacial processes in the Mestersvig region, central East Greenland

Naja Mikkelsen, Steve Carver, John Woodward and Hanne H. Christiansen

The earliest thorough investigations of periglacial processes in Greenland were conducted from 1956–1961 in the Mestersvig region (72°N 24´W) of central East Greenland, where a number of experimental sites were established by A.L. Washburn (Fig. 1; Washburn 1965, 1967, 1969). Results from these investigations are still of relevance, and are quoted in recent periglacial literature (e.g. Ballantyne & Harris 1994; French 1996).

During the field seasons of 1998 and 2000 a resurvey of Washburn's original experimental sites was undertaken. The main purpose was to describe the state of preservation of the sites and to derive estimates of long-

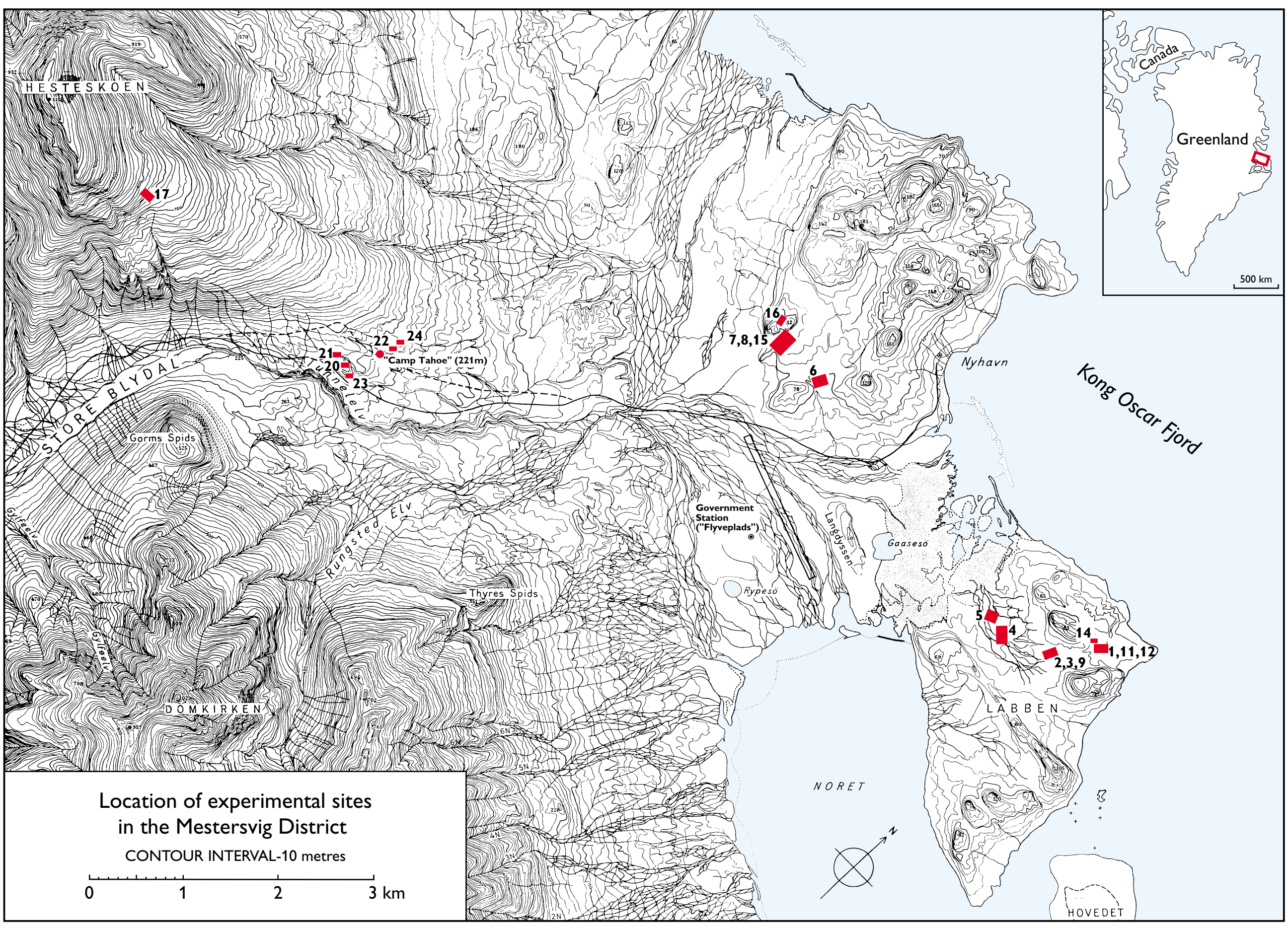

Fig. 1. Map of the Mestersvig region in central East Greenland reproduced from Washburn (1965, plate 5) with slight modifications. Locations shown as **red blocks** indicate the numbered experimental sites established by A.L. Washburn in 1956–1961. Place names on land areas of this map are in their original spelling, some of which are not in their approved modern form (correct spellings include Thyre Spids, Gorm Spids, Gåsesø and Rypesø). Mestersvig airport is here designated 'Government Station ("Flyveplads")'. On inset map the location of the Mestersvig region in central East Greenland is shown by the **red rectangle**.

Table 1. Site locations

Site 1	As for Site 11
Site 2	72°14.738'N 23°50.229'W
Site 3	25 m NE of Site 2
Site 4	72°14.642'N 23°51.200'W
Site 5	72°14.616'N 23°51.579'W
Site 6	72°14.942'N 23°57.029'W
Site 7	72°14.917'N 23°58.247'W
Site 8	72°14.945'N 23°58.187'W
Site 9	30 m NW of Site 2
Site 11	72°14.980'N 23°49.766'W
Site 12	As for Site 11
Site 14	72°14.956'N 23°49.848'W
Site 15	72°14.976'N 23°58.089'W
Site 16	72°15.035'N 23°58.261'W
Site 17	72°12.991'N 24°08.183'W
Site 20	72°13.103'N 24°03.506'W
Site 21	72°13.107'N 24°03.617'W
Site 22	72°13.361'N 24°03.075'W
Site 23	72°13.071'N 24°03.205'W
Site 24	72°13.468'N 24°03.127'W

The geomorphological sites used for field experiments and observations in 1956–1961 (Washburn 1967). Site positions were measured in 2000 using a WGS-84 conversion for the GPS positioning system. Sites 10, 13, 18 and 19 were abandoned at an early stage of the field experiments (Washburn 1967).

term (40+ years) rates of mass-wasting to compare with Washburn's original short-term rates. The field work also assessed the possibility of re-establishing some of the original sites for inclusion in a new periglacial research programme in the Mestersvig region, aimed at monitoring the impact of long-term global change on the Arctic periglacial environment in a coastal area.

Periglacial investigations in central East Greenland

The geomorphological investigations in the Mestersvig region by A.L. Washburn and coworkers included studies of frost creep and gelifluction, rock weathering and vegetation (Washburn 1965, 1967, 1969, 1973; Ugolini 1966a, b; Raup 1969, 1971). During the study period (1956–1961) Washburn established 24 experimental sites in the vicinity of the Mestersvig airfield (Fig. 1; Table 1). Each site was selected and designed to monitor periglacial processes, and to allow for comparative studies. Six of the sites (Sites 4, 5, 6, 7, 8, 17) were installed as experimental target lines, with the purpose of determining mass-wasting rates (Figs 2, 3). The observed rates of movement were subsequently related to parameters such as slope gradient, soil type, moisture and vegetation. Thermo-couples installed at Sites 6, 7 and 8 enabled ongoing registration of soil temperatures at various depths. Ambient temperature and moisture conditions were measured at all sites, and recording weather instruments were maintained at Sites 7 and 8. Additional experiments at some sites were undertaken utilising mass-wasting strain and movement-metering devices, with varying success. At experimental Site 2 a strain gauge was installed to study possible pressure build-up in connection with the formation of polygons and patterned grounds. In addition one polygon structure (close to Site 20) was excavated in the late 1950s enabling detailed study of the cross-section of the polygon.

A number of other sites were established with thin 10 cm long dowel sticks (Fig. 4) placed in well-defined patterns to study small-scale movements within patterned grounds, polygonal soil features and solifluction lobes (Sites 14, 15, 20, 21). Other dowel-stick sites allowed observations of small-scale periglacial processes on the slopes of a weathering basalt section covered by talus products (Site 16). Three sites were used for observations on the rate of exfoliation and weathering of different types of rocks (Sites 22, 23, 24). At an early stage of the field programme, Sites 10, 13, 18 and 19 were abandoned, as they were considered unsuitable for various reasons (Washburn 1967).

Detailed climatic and meteorological data were collected in conjunction with Washburn's geomorphological observations and experiments during the study period. The climate of the Mestersvig region is truly arctic with mean annual air temperature for the period 1956–1961 ranging from –9.2°C to –10.6°C, and a mean annual precipitation of 372.5 mm mostly falling as snow (Washburn 1965). Despite its location north of the Arctic Circle, Mestersvig has relatively mild, though short, summers with maximum temperatures reaching as high as 20°C in July and August (Harpøth *et al.* 1986). However, minimum temperatures can fall well below 0°C at any time during the summer season, and as such the soils in the area are clearly subject to marked freeze–thaw cycles.

The Mestersvig region is located in a zone of continuous permafrost (Christiansen & Humlum 2000), which extends to a depth of up to 125 m, while the thickness of the active surface layer ranges from 0.5 m to 2 m (Washburn 1965). Ongoing periglacial research in other parts of Greenland includes nivation studies (Christiansen 1998) and monitoring of active layer dynamics (Christiansen 1999).

Fig. 2. Close-up of target cone in mass-wasting target line at Site 5 in the summer of 2000. The 10 cm high wooden cone mounted on a wooden peg was inserted into the ground in 1956.

Fig. 3. The orange target cones of experimental Site 5 are still in line after 45 years of frost creep and gelifluction on the gently sloping hill at Labben. The pegs were originally inserted into the soil to the base of the 10 cm high cone and placed in a straight line perpendicular to the slope, with a spacing of approximately 2 m. A theodolite placed at a fixed point at the end of each target line was employed to record target movements at regular intervals over four or five seasons.

Field observations

The original experimental target lines resurveyed in 1998 and 2000 were easily identified in the field due to orange paint still being present on the target cones (Fig. 2). Of the six experimental mass-wasting lines, only Sites 4, 5 and 6 in the hills south and south-west of Nyhavn and Site 17 located on the east slope of the mountain Hesteskoen were found suitable for remeasurement (Fig. 1). Unfortunately, two important sites in the 'Nyhavn Hills' south and south-west of Nyhavn (Sites 7, 8) had been stripped of target cones by others and re-employed for later experiments. The dowel-stick sites were difficult to locate due to weathering and dispersal of the tiny sticks (Fig. 4). The pressure gauge of Site 2 was still in place, but not functioning, and the excavated profile of the polygon close to Site 20 was found to be partly slumped.

During the resurvey, measurements of target movements were recorded relative and perpendicular to the original target line. Brief descriptions of the different types of experimental sites are presented below.

Experimental mass-wasting (Sites 4, 5, 6, 17)

Experimental Sites 4 and 5 are located at altitudes of approximately 10 m and 9 m, respectively, on the Labben peninsula (Fig. 1), on a 1° to 2° gently northward-sloping surface. The area is dry and dominated by non-sorted polygons in sandy-silty clay that is almost barren of vegetation. Site 4 was established in 1956 with 30 target cones, of which 17 were considered *in situ* in 1998/2000, while at Site 5 a total of 21 of the original 27 target cones were considered to be *in situ* (Fig. 3). Preliminary estimates (by S.C.) indicate mean long-term movement rates of the order of 0.3 to 0.4 cm/yr. The general low rates are presumably due to the dryness and shallow gradient of the slope. After installation of the experimental lines, Washburn subsequently

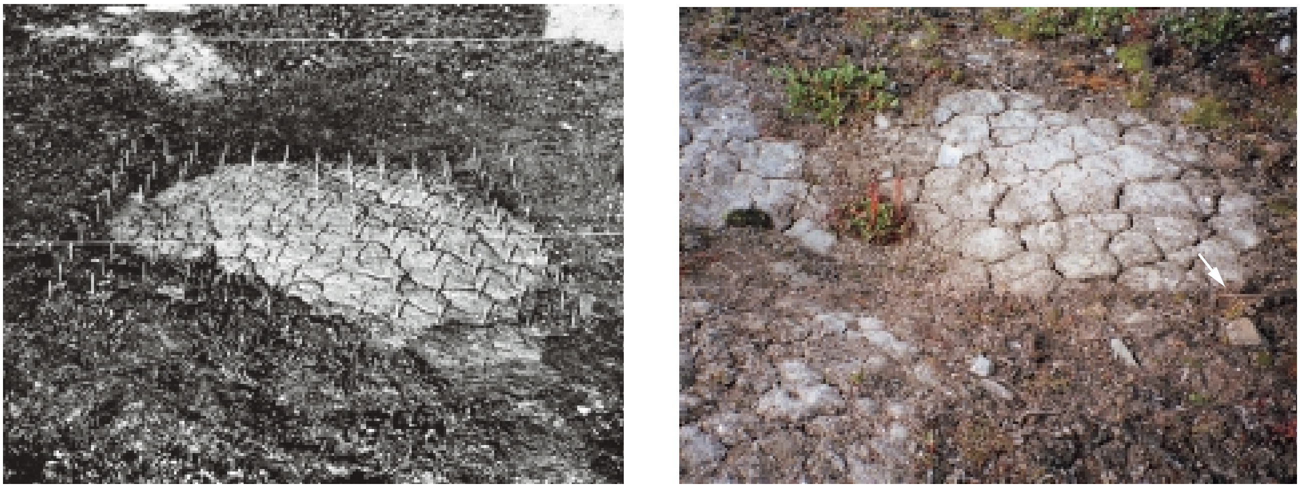

Fig. 4. Experimental Site 9 originally instrumented with short dowel sticks 0.3 cm in diameter. The dowels were spaced at intervals of 10 or 20 cm at the beginning of the experiment and inserted to depths of 5 or 10 cm in lines or grid patterns (**left**). The original dowel patterns established in the late 1950s were found to be obliterated when revisited in 2000 (**right**), due to up-freezing by the intervening freeze–thaw cycles. **Arrow** indicates one of the uprooted dowel sticks.

considered Sites 4 and 5 of limited value for detailed studies of mass-wasting, as the boulders selected for the theodolite stations were found to be subject to frost action. The target cones nevertheless provided important information on frost action such as heaving and tilting.

Experimental Site 6 is located in a N–S-trending dell south-west of Nyhavn with a gradient of approximately 3°. At the time of the 1998 and 2000 field work, a small stream traversed the valley, and the experimental area was well vegetated and characterised by wet conditions and by silty and clayey soils. Of the 43 cones installed in 1956, only 23 were considered to be in situ. Mean movement rates (estimated by S.C.) for the period 1956–1998 were about 6 cm/yr and thus slightly higher than the average short-term rate of 4.9 cm/yr calcu-

Fig. 5. Experimental Site 17 located on a gelifluction lobe on the southern slope of Hesteskoen at an altitude of 720 m. The periglacial processes at this site, which is characterised by high altitude, steep slope and wet conditions, are pronounced compared to drier sites at lower altitudes of the Mestersvig region. The two photographs from 5 August 1957 (**left**) and 22 July 2000 (**right**) show the impact of long-term periglacial processes, especially affecting the shape of the lobe front.

Fig. 6. Weathering of a tholeiitic diabase boulder at Site 22. The photograph of the rock in 1960 (**left**) was taken before a linen sheet was placed under the rock to collect weathering products for quantitative calculations on granular disintegration. **White ruler** is 17 cm long. The sheet had almost disintegrated by summer 2000 (**right**). It is evident from the two photographs taken 40 years apart that granular disintegration has been substantial in this arctic environment.

lated for the period 1956–1961 by Washburn (1967). Soil moisture would appear to have a major influence on movement rates.

Experimental Site 17 is located on a prominent gelifluction lobe at an altitude of 720 m on the east slope of Hesteskoen. The lobe has very sparse vegetation and is composed of stony diamicton and pebbles and cobbles in a clay-silt-sand matrix. The lobe is approximately 30 × 20 m in size; the upper lobe surface slopes at 15° to 23°, while the 3 m high down-slope front exceeds 45°. The lobe was originally equipped with 15 cones, of which 14 were found; however, all but three were toppled. Estimates of the average rates for long-term movement (by S.C.) were approximately 12 cm/yr, somewhat higher than the average short-term rate of 7.7 cm/yr calculated for the period 1957–1959 by Washburn (1967).

Comparisons of the outline and overall morphology of the gelifluction lobe on Hesteskoen in 1957 and 2000 show pronounced changes due to periglacial processes, notably in the shape of the lobe front (Fig. 5).

Rock weathering (Sites 22, 23, 24)

Washburn (1969) established three sites in the vicinity of 'Camp Tahoe' (Fig. 1) at altitudes of *c.* 200 m to study weathering processes of different rock types and obtain quantitative data on granular disintegration. Originally, white linen sheets were placed at the base of the boulders to collect weathering products for quantitative estimates. Sites 22 and 23 are tholeiitic diabase boulders (Fig. 6) and Site 24 a granitic boulder. Washburn (1969) concluded that granular disintegration of rocks was more widespread in polar environments than was commonly realised. The original sheets were still in place in 2000, but unfortunately so fragmented that it was impossible to collect weathering products for determination of long-term rates to compare with the short-term rates of Washburn (1969).

Patterned ground and dowel sticks (Sites 14, 15, 16, 21)

Mass-wasting and frost action on a variety of patterned ground forms were studied in detail at sites instrumented with wooden dowel sticks (Washburn 1969). The dowels are short sticks, 0.3 cm in diameter and commonly spaced at intervals of 10 or 20 cm at the experimental sites. They were inserted to depths of 5 or 10 cm in lines or grid patterns to record frost action and mass-wasting effects as measured with reference to strings or wires (Fig. 4). The original experiments showed that the maximum up-freezing that an object undergoes during a single freeze–thaw cycle is proportional to the effective object height, which is the vertical dimension of the buried portion frozen to, and therefore heaved with, the adjacent material (Washburn 1965). At the resurvey in 2000 the original dowel stick patterns established in 1956 were completely obliterated as a consequence of more than 40 years of freeze–thaw cycles.

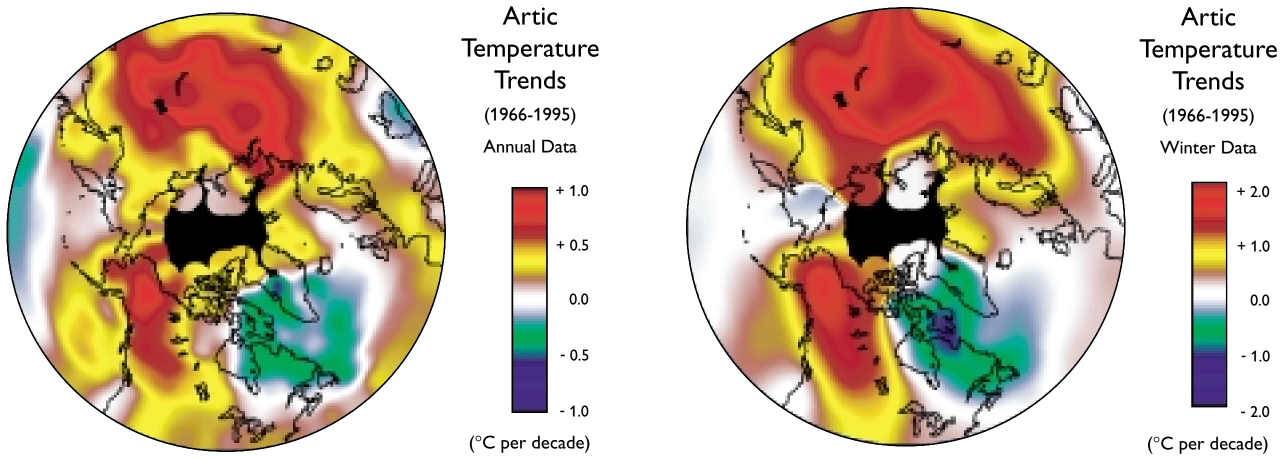

Fig. 7. Observed trends of arctic winter mean temperature from 1966 to 1995. The mean temperatures in northern and north-eastern Greenland have warmed over the last three decades, whereas the temperatures in southern Greenland show a cooling. The general temperature increase in north-eastern Greenland is considered to have had an influence on freeze–thaw cycles and thus periglacial processes in the Mestersvig region. Reproduced from IASC (1999), based on Chapman & Walsh (1993).

Preliminary results and possible effects of climate change

Interpretation of data obtained during the 1998 and 2000 resurvey is indicative of a number of problems related to the long time period elapsed between target line installation in the late 1950s and the remeasurements 40+ years later. The main difficulty lies with determining which target cones have been moved solely by the processes of frost creep and gelifluction, and which have been subject to other forces, natural or otherwise. Surface wash, particularly on the wetter Sites 6 and 17, may account for some of the longer distances travelled by toppled target cones. Some cones may also have been tilted by strong winds or influenced by human or animal activity. For example, vehicle tracks can be seen traversing Site 5. Furthermore, the data collected in 1998 and 2000 do not quantitatively distinguish between frost creep and gelifluction, but rather represent combined data on long-term mass-wasting rates for these sites.

Despite uncertainties the resurvey of all mass-wasting sites in the Mestersvig region points to some general trends. Two resurveyed sites (Sites 4, 5), both characterised by shallow gradients and fairly dry terrain, displayed very low rates of movement. The long-term rates for two other sites (Sites 6, 17), each in steeper and notably wetter terrain, showed more rapid mass-wasting rates than the short-term rates recorded more than 40 years ago.

The average global temperature has increased by *c.* 0.6°C since 1860 (Houghton *et al.* 1996) with the warmest years in the late 1990s. This temperature increase is not uniform worldwide, and regional differences also occur in Greenland (Fig. 7). Thus the average winter temperature in South-West Greenland has decreased over the last 30 years, whereas the average temperature in central East Greenland has apparently increased by approximately 0.5°C per decade during the same period. Despite all uncertainties related to the remeasured data, it is notable that the preliminary long-term mass-wasting rates (40+ years) obtained from the 1998/2000 field work are slightly higher than the short-term rates (2–5 years) obtained in the late 1950s for the wetter experimental sites with steeper slope gradients. This situation may, with some reservations, be interpreted in support of an increase in average mass-wasting rates linked to general global warming.

The detailed records of periglacial processes and mass-wasting rates in the Mestersvig region by A.L. Washburn and coworkers, together with the detailed meteorological data, provide a unique data set. These data are highly relevant to a possible new monitoring research programme and may provide insights into the longer term impact of global change on periglacial processes and on the vulnerable arctic environment.

Acknowledgements

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Projects *MINEO* and *HyperGreen*: airborne hyperspectral data acquisition in East Greenland for environmental monitoring and mineral exploration

Tapani Tukiainen

In remote sensing terminology the word 'hyperspectral' is used to distinguish sensors with several tens or hundreds of bands from the traditional 'multispectral' sensors such as Landsat TM or Landsat MSS. The success of hyperspectral techniques relies on the detection of subtle variations in the spectral properties of one or more of the components being imaged. The advances of worldwide research and development in sensor technology to achieve higher signal to noise ratios, good operational stability and improved levels of spectral and radiometric calibration have provided the instrumental basis for the deployment of this advanced technique to a number of earth resource and environmental mapping and monitoring tasks. The analysis and interpretation of hyperspectral data are extensively based on the use of spectral libraries covering a wide range of inorganic and organic natural materials and comparison of data between different areas and sensor systems.

Airborne hyperspectral data acquisition in Greenland in the summer of 2000 was carried out as part of the project *MINEO* (monitoring the environmental impact of mining activities in Europe using advanced observation techniques). This is a collaborative venture by nine European research organisations and two mining companies, with financial support from the European Community, to operate a commercial, high-quality, airborne hyperspectral scanner system (Fig. 1) for acquisition of hyperspectral data from six mining areas in Europe and Greenland (Tukiainen 2000). The area of the former lead mine in Mestersvig in central East Greenland (72°N) was selected to represent arctic environmental aspects in the *MINEO* project. The objectives of *MINEO* are to assess the application of hyperspectral techniques for pollution detection and monitoring in a wide range of mining environments.

The hyperspectral data acquisition mission in Greenland was extended to acquire data for project *HyperGreen*, a mineral exploration programme of the Geological Survey of Denmark and Greenland (GEUS), financed by the Bureau of Minerals and Petroleum, Greenland. The objectives of *HyperGreen* are to assess the applicability of high spectral resolution imaging spectroscopy as a mineral exploration tool. The *HyperGreen* project also included a target flown for the National Environmental Research Institute, Denmark (DMU). The original survey targets of project *HyperGreen* were located in West Greenland, but were cancelled due to weather constraints and the limited availability of the HyMap™ system (Cocks *et al.* 1998). Six alternative areas in central East and North-East Greenland with a variety of known mineral occurrences (Harpøth *et al.* 1986) and potential for new occurrences were therefore surveyed (Fig. 2).

Airborne hyperspectral imaging system

HyVista Corporation, Australia, was selected as the contractor for the airborne hyperspectral data acquisition. A Dornier 228 aircraft, operated by Deutsches Zentrum

Fig. 1. HyMap™ imaging spectrometer installed on a Dornier 228 aircraft.

Geology of Greenland Survey Bulletin 189, 122–126 (2001)

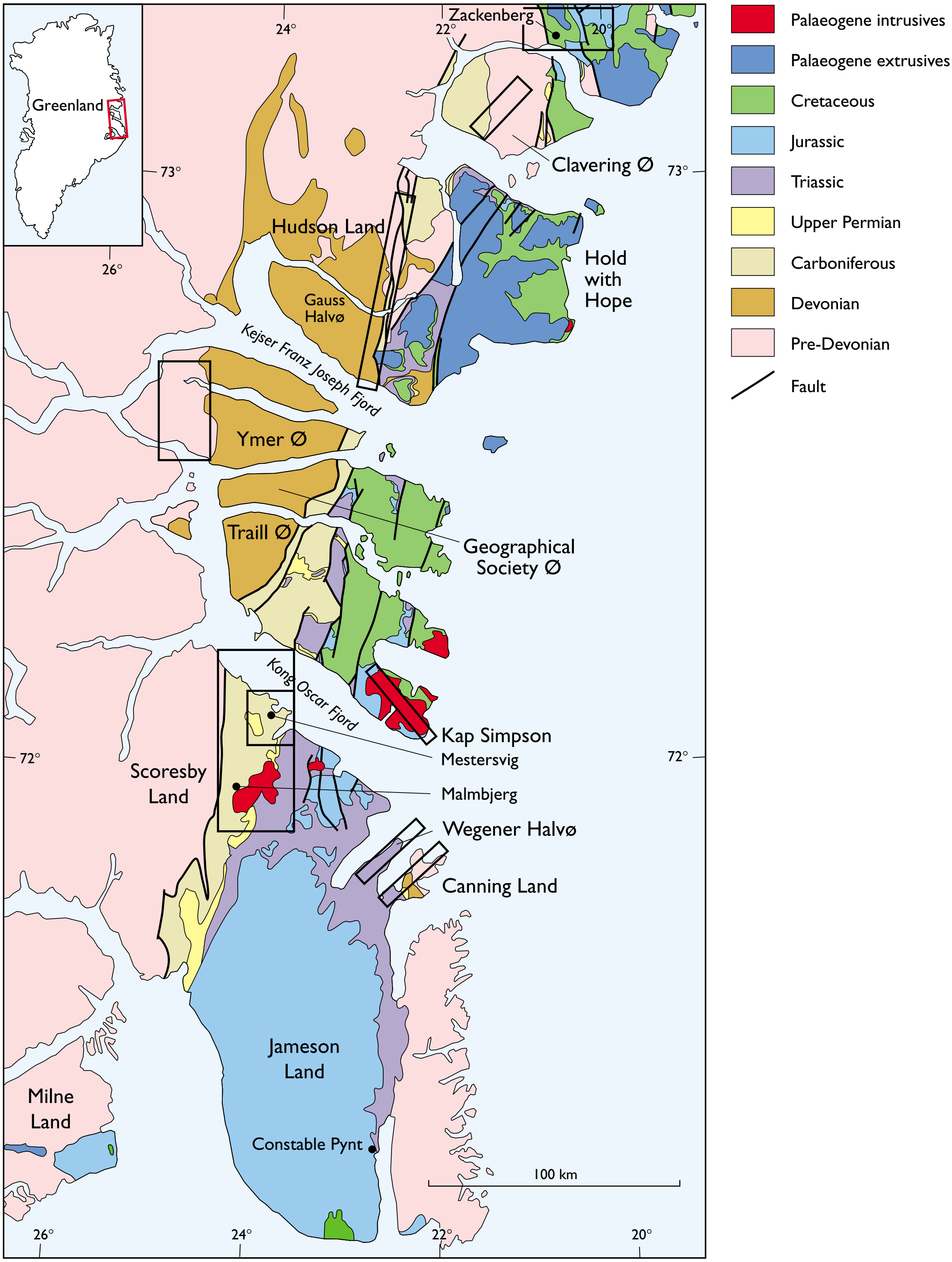

Fig. 2. Simplified geological map of central East and North-East Greenland. Modified from Stemmerik *et al*. (1997). The areas where airborne hyperspectral data were acquired are indicated by **black frames**.

Table 1. Spatial and spectral characteristics of HyMap™ sensor

Spatial configuration			
Instant field of view (IFOV)	2.5 mr along track 2.0 mr across track		
Field of view (FOV)	60 degrees (512 pixels) Swath 2.3 km at 5 m IFOV (along track) 4.6 km at 10 m IFOV (along track)		
Spectral configuration			
Module	Spectral range	Average spectral sampling interval	Number of bands
VIS	450–890 nm	16 nm	30
NIR	890–1350 nm	13 nm	32
SWIR1	1400–1800 nm	12 nm	32
SWIR2	1950–2480 nm	16 nm	32

mr = milliradian
nm = nanometre

Table 2. Summary of hyperspectral data acquisition programme in central East and North-East Greenland

Survey area	Project	Number of flight lines	Line km
Canning Land	*HyperGreen*	5	165
Mestersvig	*MINEO*	10	197
Malmbjerg	*HyperGreen*	15	695
Ymer Ø	*HyperGreen*	6	186
Hudson Land	*HyperGreen*	5	232
Clavering Ø	*HyperGreen*	1	25
Zackenberg	DMU/*HyperGreen*	12	360
Kap Simpson	*HyperGreen*	2	64

für Luft und Raumfart, e.V., Germany, provided the platform for the HyMap™ hyperspectral imaging spectrometer (Fig. 2) and a Zeiss RMK A 15/23 aerial camera; the latter was used for simultaneous aerial photography to obtain stereoscopic coverage for the production of digital terrain models.

The HyMap™ hyperspectral scanner manufactured by Integrated Spectronics Pty Ltd., Australia, has four spectrometers covering the interval from 450 to 2450 nanometres (nm), excluding the two major water absorption windows (Table 1; Cocks *et al.* 1998). The sensor operates in a 3-axis gyro-stabilised platform to minimise image distortion due to aircraft motion. The signal/noise ratio measured outside the aircraft with a sun angle of 30° and 50% reflectance standard is more than 500/1, except near the major atmospheric water absorption bands.

Geo-location (longitude, latitude and altitude) and scanner attitude (roll, pitch and true heading) data to provide the necessary information for image geo-coding were acquired with a differential GPS satellite navigation system (DGPS) and an integrated inertial monitoring unit. The scanner operations required that the three detectors for the near infrared (NIR) and short-wave infrared region (SWIR1, SWIR2) had to be cooled to 77°K using liquid nitrogen. Approximately ten litres of liquid nitrogen were consumed for each full day of data collection.

Survey areas

Flight operations in Greenland in 2000 commenced on 5 August and were completed on 11 August. Eight target areas reached from airfields at Mestersvig and Constable Pynt (Fig. 2; Table 2) were surveyed with the following survey specifications:

IFOV ('pixel size')	5 m
Overlap per line	20%
Approximate ground speed	150 knots (277 km/h)

For the HyMap™ instrument the instant field of view (IFOV) of 5 m corresponds to a flight altitude of 2500 m (8200 ft) at which the scanner's swath width (the area to be imaged across the flight track) is approximately 2.3 km (Fig. 3). For the more mountainous areas, the flight altitude was determined from the local topographic baselevel.

Data processing and analysis

By the end of the year 2000 the contractor had delivered flight line radiance data ('at sensor radiance'), spectral and radiometric calibration data for the HyMap™ sensor and the geo-location and scanner attitude data. The data will be subjected to atmospheric and geometric corrections to provide the basis for detailed analysis. The final processing of the data to extract spectral end members ('mineral mapping', vegetation types and vegetation stress) and map their locations and abundances will be based on advanced algorithms developed for the analysis of hyperspectral data (Goetz *et al.* 1985; Boardman & Kruse 1994).

The large volume and complexity of the data generated by the hyperspectral sensors mean that the classification techniques to analyse the multispectral data, based on euclidean distance between groups of data (classes), are computationally cumbersome. A variety of interpretation techniques have therefore been developed in the last ten years. The most popular of these is the selection of 'end members' from hyperspectral data. This technique is based on the assumption that the imagery is composed of mixed pixels ('mixels'), each pixel resulting from an integrated measurement over a multicomponent pixel to form a composite spectrum. A composite spectrum is formed by linear combinations of individual spectra ('pure' or single component spectra). The extraction of spectral end members will be undertaken using a variety of 'spectral unmixing' algorithms.

Conclusions and outline of future work

High-quality airborne hyperspectral data totalling 1924 line km were acquired from eight localities in central East and North-East Greenland, using an advanced hyperspectral imaging spectrometer with 126 narrow bands covering the spectral range from 450 nm to 2480 nm. The hyperspectral data will be used to assess the application of hyperspectral techniques to environmental monitoring and mineral exploration.

Field follow-up will be carried out for both *MINEO* and *HyperGreen* projects in the summer of 2001, and will be concentrated on selected areas considered representative for the assessment of the objectives of the two projects.

An international team from the *MINEO* consortium will undertake follow-up and baseline studies on environmental indications emerging from the processing of the *MINEO* data by GEUS and the *MINEO* partners. The final results and conclusions will be included in the final report of the *MINEO* project which is planned for the end of 2002.

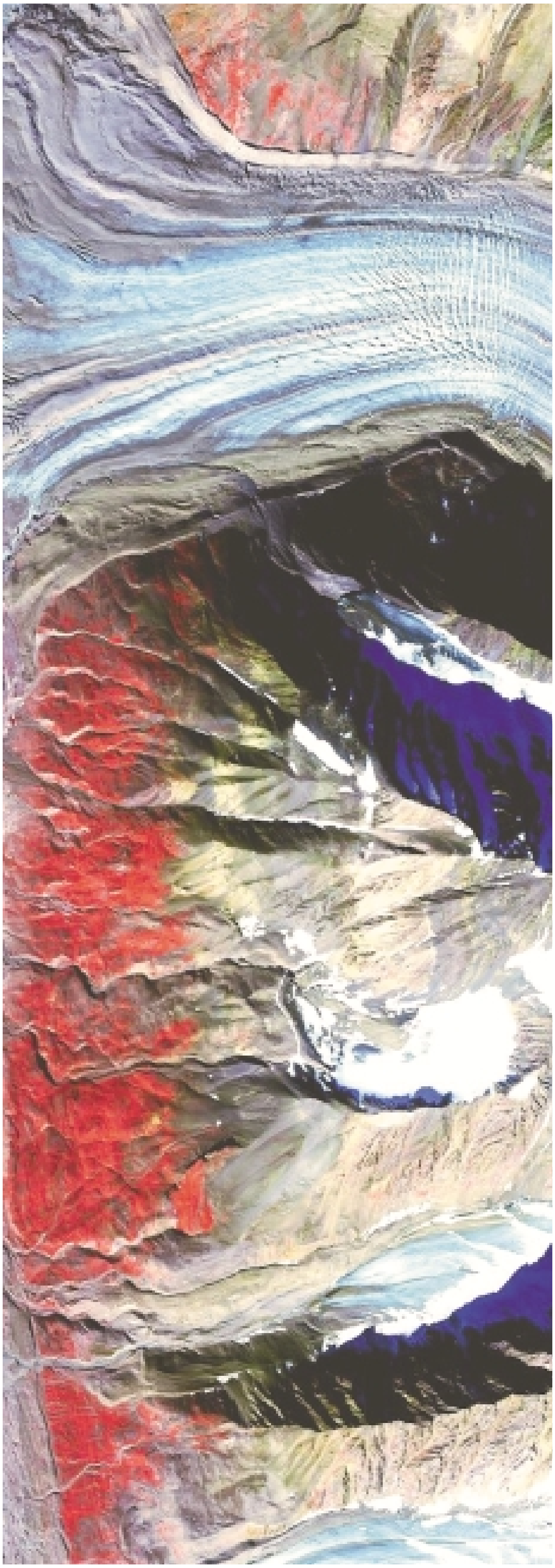

Fig. 3. False colour 'quicklook' of HyMap^{TM} data from a flight line at the west edge of the Mestersvig survey block. The striped lithologies are sediments of the Neoproterozoic Eleonore Bay Supergroup. Bright red colours are vegetation-rich areas. The N–S strip (top to bottom) covered by the flight line is about 2.3 km wide.

For the *HyperGreen* project, the known mineral occurrences, some associated with spectacular hydrothermal alteration hosted by a wide range of igneous and sedimentary lithologies (e.g. Malmbjerg molybdenum deposit, Fig. 2), will provide a good reference base for the evaluation and assessment of hyperspectral data processing techniques in mineral exploration and geological mapping in arctic environments.

It is expected that the statistical treatment of the *HyperGreen* data by GEUS will locate new targets with mineralogical characteristics (in terms of specific rock alteration phenomena or direct detection of ore minerals) related to the presence of potentially economically interesting mineral occurrences.

In order to assess the discriminative power of this novel technique, follow-up ground spectroradiometric measurements will be carried out on known and new targets. These will be chosen to represent a wide range of mineralisation types and rock lithologies. The results of this work are expected to be available during 2002.

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Studies of sea-ice conditions north of Greenland: results from a pilot *GRASP* initiative on the extension of territorial limits into the Arctic Ocean

Naja Mikkelsen, Preben Gudmandsen and René Forsberg

The continental shelf and Arctic Ocean north of Greenland are located in one of the least investigated regions of the Arctic. Even basic data on bathymetry are known only in rudimentary form from historical expeditions, a few scientific ice-floe stations and ice-breaker traverses, and from rare United States and Russian map compilations. No official Danish nautical charts of the region exist, and it is only within the last 20 years that the coastline of North Greenland facing the Arctic Ocean has been precisely mapped.

Interest in the region has increased in recent years through major international efforts such as scientific submarine expeditions (SCICEX), major airborne geophysical surveys and the release and compilation of formerly classified oceanographic, hydrographic and climate-related data. Analyses of data from the submarine cruises have indicated a thinning of the polar sea-ice cover (Rothrock *et al.* 1999).

Another reason for interest in the Arctic Ocean is the possibility for nations bordering the Arctic Ocean to claim an extension of their territorial limits beyond 200 nautical miles (nm) as a consequence of the UN Laws of the Sea Convention (United Nations 1993).

Danish research activities in the Arctic Ocean north of Greenland have been restricted to participation in a few international ice-floe scientific stations or ice-breaker expeditions, and recently in airborne geophysical surveys. However, airborne measurements can only address a limited number of scientific questions and a broader research effort north of Greenland to gain information on this poorly known region is therefore needed.

Any Danish/Greenlandic claim for an extension into the Arctic Ocean of the current 200 nm territorial limit must be supported by basic data sets on hydrography and geology, and in this context the Commission for Scientific Research in Greenland initiated in 1998 a dis-

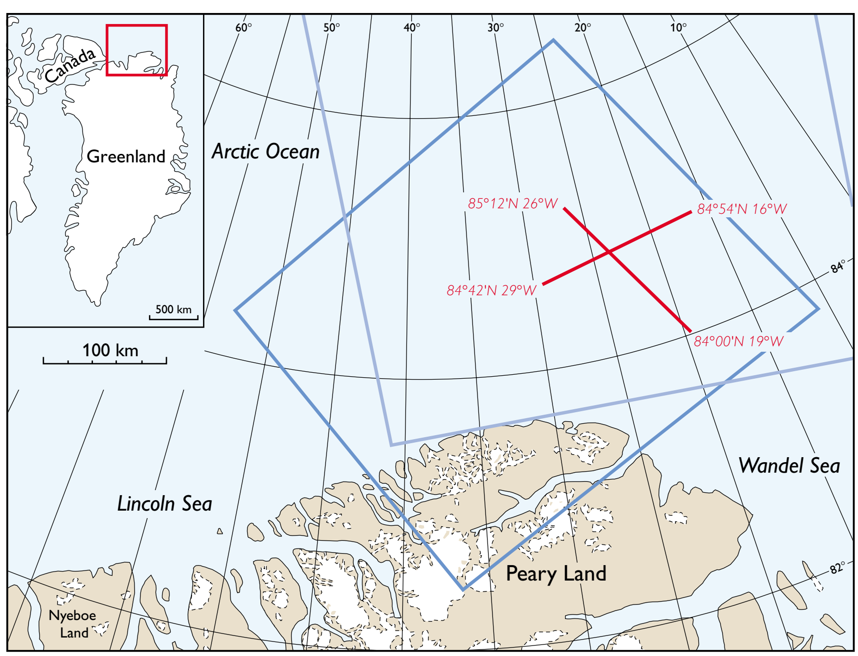

Fig. 1. Map of northernmost Greenland and adjacent Arctic Ocean with the two flight lines from 7 March 2000 shown in **red**, and the Radarsat scenes acquired on 6 and 12 March 2000 shown in **dark blue** and **light blue**, respectively.

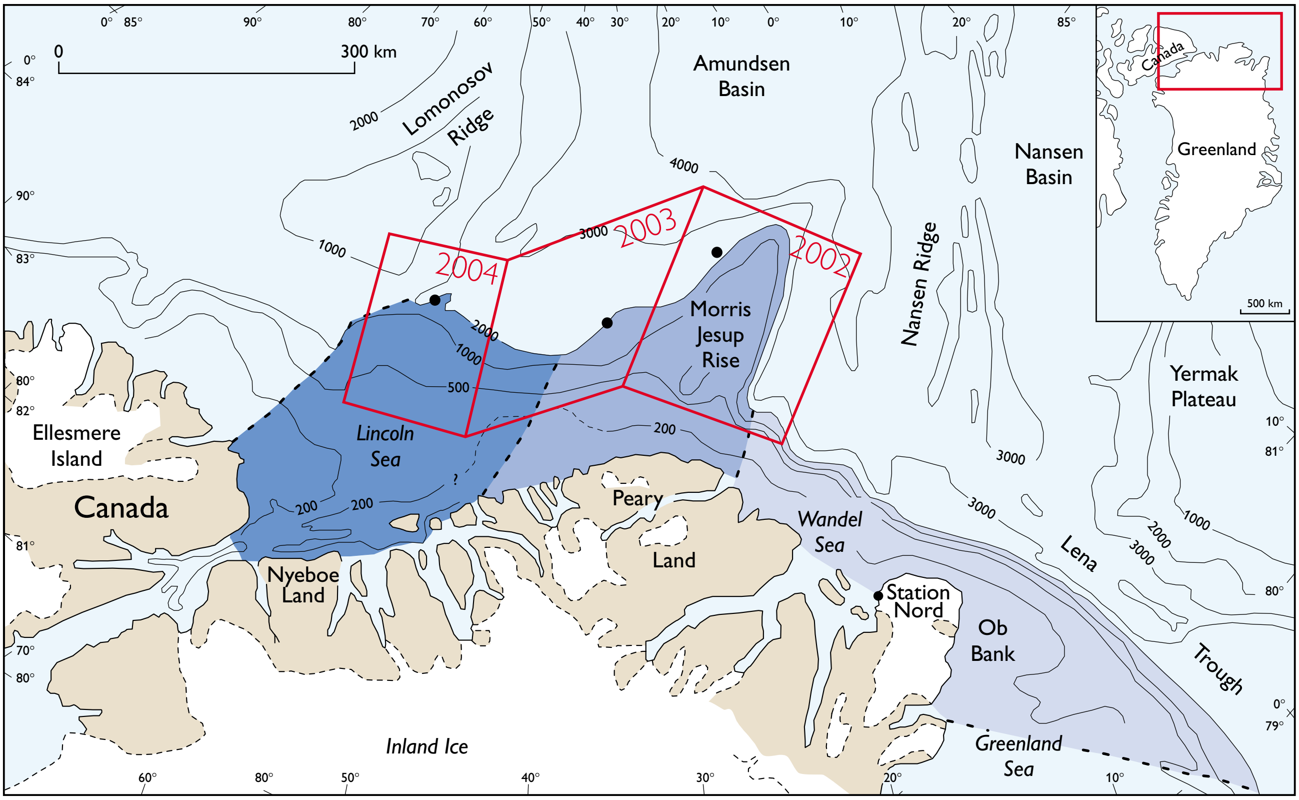

Fig. 2. North Greenland continental margin with main physiographic regions (Lincoln Sea, Morris Jesup Rise, Wandel Sea) shown in **blue tones**. Modified from Dawes (1990). Location of the ice-drift camps proposed by *GRASP* for 2002, 2003 and 2004 are shown by **black dots** in the **framed areas**. Bathymetric contours are in metres.

cussion on the scientific exploration of the region. A science plan was drafted in response (Forsberg *et al.* 1999) and a project, the *Greenland Arctic Shelf Project* (*GRASP*), was proposed.

This paper summarises results from a pilot *GRASP* initiative with airborne and satellite observations of sea-ice conditions north of Greenland in order to investigate the feasibility of establishing ice-floe camps (Fig. 1). These camps will collect a wide array of scientific data including data relevant to a possible claim with respect to territorial limits north of Greenland.

Geological setting

The main physiographic and geological features include the Lincoln Sea shelf, Morris Jesup Rise and the Wandel Sea Basin, as well as the deeper ocean basins north and north-east of these features (Fig. 2). The Lincoln Sea shelf represents a little-known but seismically active sedimentary basin of Palaeozoic and Mesozoic–Cenozoic strata (Dawes & Peel 1981). Morris Jesup Rise is an aseismic bathymetric feature of probably mixed oceanic and continental origin (Dawes 1990), while the Wandel Sea is characterised by a seismically active and unusually narrow continental shelf margin. Geological information on these pronounced morphological features is very sparse, as is information on hydrography and shelf configuration. Morris Jesup Rise is of special interest as it extends far north into the Arctic Ocean and may therefore play an important role in future discussions on territorial boundaries.

GRASP objectives

In order to meet the challenge of both the scientific and potential political interests in the Arctic Ocean north of Greenland (Taagholt & Hansen 2001), the *GRASP* science plan suggests acquisition of data on bathymetry, shelf slope, geology, geophysics, oceanography and sea ice (Forsberg *et al.* 1999). Oceanographic depth data and geological data on sediment distribution and thickness are of particular importance. The science plan

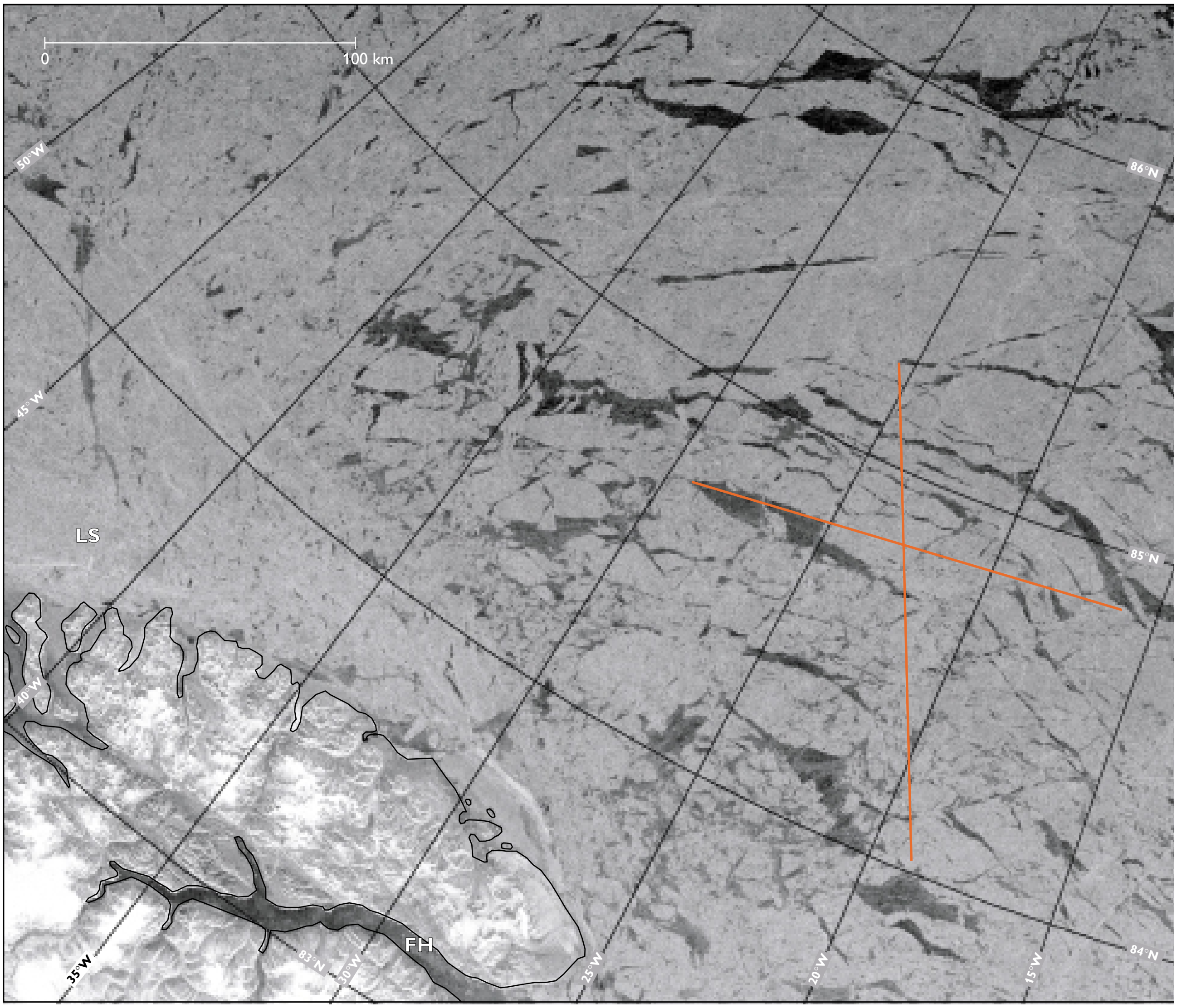

Fig. 3. Radarsat scene acquired on 6 March 2000 showing an area of the sea-ice covered Arctic Ocean measuring 500 × 500 km. Northernmost Greenland (Peary Land) with Frederick E. Hyde Fjord (**FH**) marked. An E–W-trending feature in the sea-ice along latitude 84°N indicates the boundary between the faster moving ice of the main central Arctic Ocean gyre and the stationary or slow moving sea ice of the Lincoln Sea region (**LS**). The C-130 flight lines from 7 March 2000 are indicated in **red** over Morris Jesup Rise.

proposes that data acquisition be undertaken from floating ice camps deployed above the 2000–2500 m water-depth contour (Fig. 2), and supported by helicopter and Twin Otter aircraft. This operation would allow collection of data covering crucial parts of the shelf region from the Wandel Sea in the east to the Lincoln Sea in the west, with special emphasis on Morris Jesup Rise. The ice stations are planned to be deployed in March or April 2002, 2003 and 2004, allowing at least a one-month operation period before the summer melt.

Of particular scientific interest is the present-day thinning of the Arctic Ocean sea-ice cover detected from submarine investigations (Johannessen *et al.* 1999; Rothrock *et al.* 1999; Wadhams & Davis 2000); data indicates a thinning of 30 to 40% from the 1970s to the 1990s. A continued future decrease in ice thickness is of importance for global commerce and shipping, and not least for possible effects on the fragile Arctic ecological systems.

Airborne observations March 2000

A reconnaissance flight in March 2000 north of Greenland was the first field campaign of the *GRASP* initiative. The purpose of the flight was to study the sea-ice conditions that may be encountered when the planned ice stations are operated. The observations from the air facilitated interpretation of satellite images acquired in the same period.

The aerial reconnaissance was made on 7 March from a C-130 aircraft of the Royal Danish Air Force on a supply mission to Station Nord. Two flight lines were undertaken crossing Morris Jesup Rise, close to the location of the first ice camp planned for 2002 (Figs 1, 2). Digital video observations were made from the flight deck and photographs taken with a hand-held camera at regular intervals. The weather conditions were not optimal for the mission, as fog and haze partly covered the region, but the data acquired and subsequent studies have provided relevant information for future *GRASP* initiatives.

It was evident from the observations that the sea-ice cover over Morris Jesup Rise was irregular. Large areas of multi-year ice were intersected by leads with newly formed ice, and in some cases open water appeared in leads of 50–75 m width. Some of the major ice floes, with a size of several square kilometres, appeared from the air to be infiltrated by seawater beneath the snow cover.

Satellite observations

Observations from the flight reconnaissance were compared with data from satellite scenes acquired on 6 and 12 March 2000 by the Canadian satellite Radarsat (Fig. 1). The satellite scenes covered a wide region, including the area of the flight lines together with the area to the north-west that constitutes the source of sea ice transported over Morris Jesup Rise by the Transpolar Current.

Data from the radar scenes and aerial observations complement each other. It appears from the radar scenes that many large floes of multi-year ice were interspersed by leads that were covered by newly formed ice (Fig. 3) under the influence of the prevailing low temperatures. The patterns of wide and large ice-covered leads north and east of Morris Jesup Rise changed very little between 6 and 12 March, indicating that they had been formed in a period prior to the flight. Based on displacements of ice features recognised in the two radar scenes, a drift velocity of 2 km/day towards 110° was determined, a direction almost parallel to the North Greenland coast. There appeared to be a slight compression of the ice-coated leads in the six-day period between the two radar acquisitions.

Ice patterns and the refrozen leads observed from the aircraft and captured by the photographs were compared with features seen on the radar scenes. Radar waves penetrate the snow cover of the floes and show the ice-surface conditions, whereas the visual observations show the snow surface. However, with a spatial resolution of only 100 m, the radar scenes did not reveal the narrow leads and ice ridges observed from the aircraft. Airborne observations are therefore required in conjunction with Radarsat data when planning the position of future ice camps.

These preliminary data, together with satellite data from previous years, show that in order for a scientific sea-ice station to pass over the centre of Morris Jesup Rise while collecting data, the station should be deployed at about 85°N 24´W, and would need about two months to drift across the Morris Jesup Rise.

Conclusions

Analyses of Radarsat images and airborne observations of ice conditions north of Greenland have provided a set of preliminary data on ice conditions and ice dynamics which is important for the planning of future *GRASP* initiatives and ice camps. Additional aerial observations and remote sensing studies will be undertaken in 2001 to obtain a firmer impression of the sea-ice conditions. These will be planned to show any systematic variation of ice conditions, and they may also add valuable information to the ongoing discussion of global climate change. Data obtained from ERS satellites from the period 1991–2000 will be analysed with this in mind.

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