GEOLOGY OF GREENLAND SURVEY BULLETIN 183 • 1999

Review of Greenland activities 1998

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

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Edited by
A. K. Higgins and W. Stuart Watt

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Cover
The area around the head of Søndre Strømfjord has been known for some time to contain saline lakes. The salinity in these closed-basin lakes has resulted from evaporation during the Holocene and as a result the sediments can be used as climate archives. The sediments in some of these lakes are laminated and it is easier to take cores when the lakes are frozen (see Anderson *et al*. this volume). The photograph shows returning from Store Saltsø, one of the saline lakes in the area, after a day's coring. The fossil shorelines around the lake are highlighted by the snow in the background. Photo: N.J. Anderson.

Frontispiece: facing page
The Apparsuit promontory south-east of Upernavik seen from the deck of M/S *Sila* during the 1998 reconnaissance for mineral occurrences in North-West Greenland (see Thomassen *et al.* p. 39). The promontory, 540 m high, is composed of exfoliated granite belonging to the 1.86 Ga Prøven igneous complex and hosts an important bird cliff, as can be seen from the coloration. The field work was a joint project between the Survey and the Bureau of Minerals and Petroleum, Government of Greenland.

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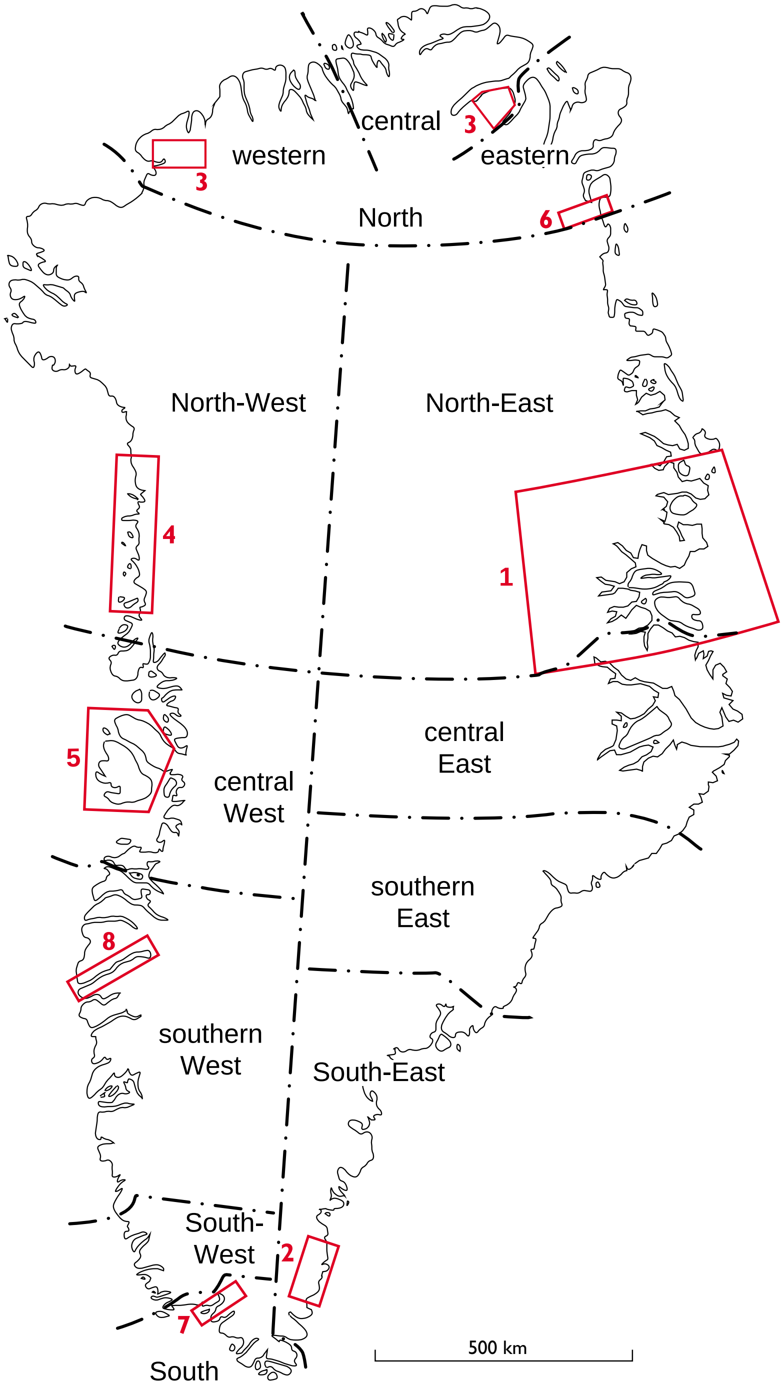

Locality map for contributions in this Review of Greenland activities. Numbers locate the eight scientific papers in the table of contents opposite; the Director's review introducing this volume deals with the whole of Greenland.

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A review of Greenland activities, 1998

Kai Sørensen
Director

Field activities in Greenland by the Geological Survey of Denmark and Greenland (GEUS) were at a high level in 1998, involving 122 persons including 23 from the Danish Lithosphere Centre (DLC); these figures include guest researchers within and outside Denmark. This year, the Survey's normal total staff, in terms of man-years, amounted to 362; of these, 98 were focused on Greenland-related activities. DLC, whose activities up to now have largely been concerned with research in Greenland, has a normal staff of 21 persons.

GEUS activities are primarily funded by the Danish state through a Finance Law grant, of which 35 million DKK were ear-marked for Greenland activities in 1998. In addition funding for resource-related activities is provided by the Government of Greenland (18 million DKK) via the Bureau of Minerals and Petroleum (BMP) in Nuuk, which took over administrative responsibility for energy and mineral resources on the 1st of July 1998.

General scientific activities are made possible by funding from a variety of sources, national, as well as international: the Danish Natural Science Research Council, the Commission for Scientific Research in Greenland, the Carlsberg Foundation, the European Union, the Government of Greenland (through the BMP), and others. Scientific funding agencies contribute significantly to earth science activities in Greenland. Total funding for Greenland activities in 1998 thus amounted to 84 million DKK. The Danish Lithosphere Centre, funded by a grant from the Danish National Research Foundation (Grundforskningsfonden), is administratively linked to the Survey but housed in the buildings of the University of Copenhagen.

General scientific activities are often co-operative ventures between GEUS and national as well as international universities and research establishments. Co-operation with institutions in Greenland are particularly important. In 1998, the Greenland National Museum and Greenland Field Investigations (Asiaq) participated in the Survey's scientific activities.

Through its representative on the Board of GEUS, the Government of Greenland is directly involved in setting priorities for the Survey's activities. GEUS had two geologists seconded to the BMP in Nuuk throughout 1998 to assist in its work concerning mineral and petroleum exploration. BMP and GEUS jointly supported initiatives to inform the international oil and mineral industries about opportunities in Greenland through publication of the newsletters *Ghexis Newsletter* and *Greenland MINEX News*, and through participation in conferences in Europe and North America with publicity stands, lectures and posters.

Geological mapping

The Survey's mapping project in North-East Greenland between latitudes 72°N and 75°N was initiated in 1997 with the emphasis on compilation of a 1:500 000 scale map (sheet 11, Kong Oscar Fjord; Fig. 1, **1**) and the field activities by an expedition group totalling 43 persons were completed in 1998. The 29 geologists and ten student assistants included a DLC party of two working with Paleogene basalts, several teams studying post-Caledonian basins (Tupolar project), and mineral resource investigations (see also below). This now classic area of North-East Greenland was originally mapped during Lauge Koch's expeditions before and after the Second World War. Developments in geological techniques, notably the advent of absolute dating methods, have necessitated a systematic re-mapping, with the focus on interrelationships between reworked basement complexes and Neoproterozoic and Early Palaeozoic sediments. The timing of granite formation and emplacement has also been the subject of reassessment. During the 1998 field work logistic support was given to a Cambridge University field party which visited some of the classic Devonian vertebrate localities,

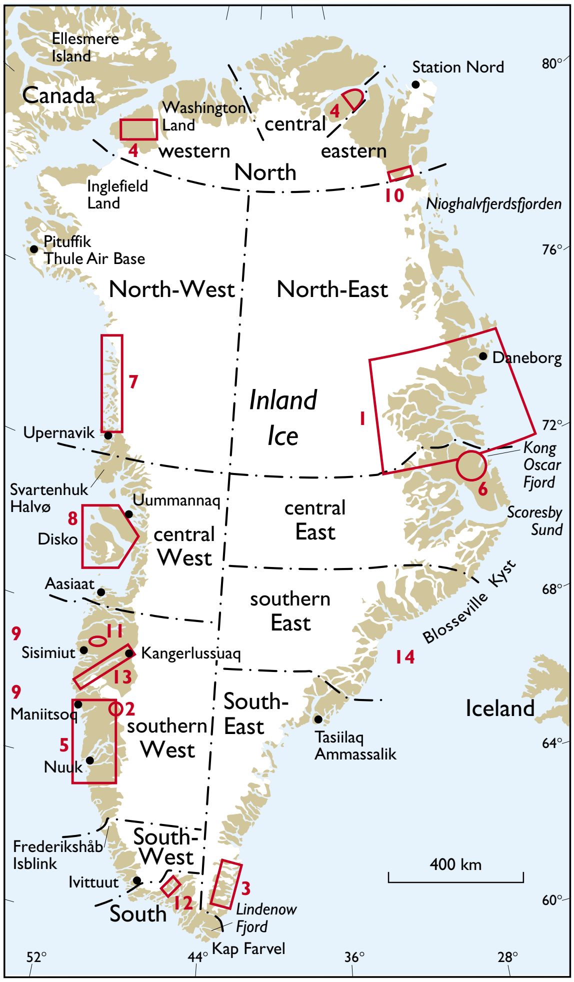

Fig. 1. Survey activities in Greenland in 1998. **1**: Regional geological mapping, North-East Greenland. **2**: Studies of the early crust of the Earth at Isua. **3**: Plate tectonics and the Julianehåb batholith. **4**: Aeromagnetic survey, Washington Land and J.C. Christensen Land. **5**: Aeromagnetic survey, Nuuk to Maniitsoq. **6**: Ore geological studies, Mestersvig. **7**: Ore geological studies, Upernavik. **8**: Hydrocarbon studies, Nuussuaq Basin. **9**: Marine seismic re-interpretation, offshore West Greenland. **10**: Glaciological and palaeoclimatic studies, Nioghalvfjerdsfjorden. **11**: Snow hydrological investigations, Sisimiut. **12**: Palaeoclimatic data acquision. **13**: Palaeoclimatic data acquision, Kangerlussuaq (Søndre Strømfjord). **14**: Danish Lithosphere Centre drilling operations, offshore East Greenland.

and to four groups of geologists from the University of Oslo with whom co-operation has been established.

Field activities in the Isua region north-east of Nuuk, West Greenland (Fig. 1, **2**) continued, with the second field season of a three-year programme aimed at sampling and mapping of the very early Archaean Isua supracrustal belt. This work is undertaken in co-operation with a number of institutions within and outside Denmark, and is primarily funded by the Danish Natural Science Research Council.

In South-East Greenland work continued on the elucidation of the plate tectonic processes during the Palaeoproterozoic Ketilidian orogeny. Studies in 1998 concentrated on the margins of the Julianehåb batholith (Fig. 1, **3**) with the purpose of improving models of its emergence. The project was carried out as a joint project with Kingston University, England, and the Danish contribution was funded by grants from the Carlsberg Foundation and the Danish Natural Science Research Council.

Mineral resource investigations

The Survey's ongoing airborne geophysical programme, financially supported by the BMP, was continued at a high level in 1998. The main aim of the project is to acquire data of interest to the mining industry and thus encourage commercial prospecting.

The final survey of a planned five-year programme 'AEM Greenland' was completed in 1998, and comprised magnetic and electromagnetic data acquisition over Washington Land and J.C. Christensen Land in respectively western and eastern North Greenland (Fig. 1, **4**). In addition, an aeromagnetic survey, 'Aeromag 98', was flown over the region between Nuuk and Maniitsoq in West Greenland (Fig. 1, **5**).

As part of the North-East Greenland mapping project field parties investigated mineralisation showings, in particular along fault zones, as well as carrying out follow-up studies of anomalies detected by the 1997 magnetic and electromagnetic survey flown south of Mestersvig, in the sediments of the Jameson Land Basin (Fig. 1, **6**).

A mineral resource investigation carried out in the Upernavik district of North-West Greenland (Fig. 1, **7**) encompassed collection of stream sediments and visits to, and sampling of, mineralisation localities. This work was undertaken in co-operation with, and was funded by, the Bureau of Minerals and Petroleum.

Petroleum geology

The search for, and sampling of, oil seeps in the volcanic rocks of the Disko – Nuussuaq – Svartenhuk

Halvø region of central West Greenland continued in 1998 (Fig. 1, **8**). General studies of structural geology, sedimentology and biostratigraphy, together with studies of the volcanic sequence, were undertaken as part of the activities in the onshore parts of the Nuussuaq Basin. A major re-interpretation of the basin was concluded, tying together onshore field observations and offshore seismic reflection, magnetic and gravimetric data aiming at an understanding of the pre-basaltic tectonics and basin configuration. A study of the uplift history of the basin, funded by a grant from the Danish Energy Agency (DEA) of the Ministry of Environment and Energy (EFP – Energy Research Programme), was concluded and reported in 1998.

A major re-interpretation of the seismic data offshore southern West Greenland was initiated, incorporating data acquired over the past few years, together with a re-analysis of the biostratigraphy of the offshore wells drilled in the late 1970s (Fig. 1, **9**). After the transfer of the resource administration to Nuuk the formulation of a new oil and gas exploration strategy was initiated in the second half of 1998. This work is undertaken as a joint effort between BMP, GEUS and the DEA.

General scientific activities

A research project studying the dynamics of the floating ice tongue filling Nioghalvfjerdsfjorden in eastern North Greenland was continued in 1998 (Fig. 1, **10**). Through radar and seismic measurements the thickness of the floating glacier front and the bathymetry of the fjord were investigated in co-operation with the Danish Centre for Remote Sensing and the German Alfred Wegener Institute. Submarine melting of the floating ice has been shown to be of particular importance in assessing correctly the mass balance of floating glaciers. Sampling of marine and lake sediments has also been undertaken in order to obtain palaeoclimatic data from the region. Snow hydrological investigations were also carried out north-east of Sisimiut in West Greenland with the purpose of studying the processes leading to discharge from a hydrological basin with hydroelectric potential (Fig. 1, **11**).

In the fjords Tunulliarfik and Igaliku Fjord in South Greenland (Fig. 1, **12**) marine investigations were carried out in order to acquire palaeoclimatic data relevant to the question of the disappearance of former Norse settlements, and to locate, for example, possible shipwrecks and other artifacts of Norse origin.

Lake sediments were sampled for palaeoclimatic studies in several lakes between Kap Farvel and Frederikshåb Isblink in south-western Greenland, as well as in lakes in the Kangerlussuaq (Søndre Strømfjord) area of southern West Greenland (Fig. 1, **13**).

The DLC drilling operation offshore southern East Greenland (Fig. 1, **14**) did not meet its 1998 objectives due to technical problems. DLC researchers also participated in the Survey's activities in North-East Greenland (Fig. 1, **1**) and in the Isua area of southern West Greenland (Fig. 1, **2**).

Publications

In 1998 the Survey published three issues in the *Geology of Greenland Survey Bulletin* series (nos. 175, 179 and 180), of which no. 180 (24 articles) provides a review of the Survey's activities in 1997. In *Geology of Denmark and Greenland Map Series CD*, four CD-ROMs were released of previously published 1:500 000 maps of the national map sheet coverage. The first digitally produced 1:100 000 map sheet (Lindenow Fjord) was also published in 1998. Thematic maps of Inglefield Land, North-West Greenland, previously published in paper form in 1996, were released on CD-ROM. Two series of maps based on airborne geophysically acquired data from two regions were issued during the year: one covers the Disko Bugt – Nuussuaq region central West Greenland (Aeromag 1997) and the other the northern part of Jameson Land, central East Greenland (AEM Greenland 1997).

In the series *Danmarks og Grønlands Geologiske Undersøgelse Rapport,* 18 issues with a 'Greenland content' were published. Two issues of the newsletter directed towards the oil industry (*Ghexis Newsletter* 13 and 14) and two issues of the newsletter directed at the mining industry (*Greenland MINEX News* 14 and 15) were published in 1998. The Survey's activities in Greenland, including those of DLC, have resulted in the publication of 45 papers in international scientific outlets.

A list of publications in English released in 1998 concludes this volume on pages 75–81.

Conclusion of the 1:500 000 mapping project in the Caledonian fold belt in North-East Greenland

Niels Henriksen

The second and last field season of the mapping project in the southern part of North-East Greenland (72°–75°N) was carried out in 1998 with full accomplishment of all planned goals. The general overview mapping of the East Greenland Caledonian fold belt has now been completed, in total covering a stretch of more than 1300 km between latitudes 70°N and *c.* 81°30´N (Fig. 1). The Survey's systematic regional 1:500 000 mapping programme in the East Greenland Caledonides started with mapping in the Scoresby Sund region (70°–72°N) in 1968, and in the course of 13 field seasons spread over 30 years has involved more than 50 geologists for one or more field seasons each; several Survey geologists have participated in all 13 field seasons. The mapping of the Caledonian fold belt and the adjacent pre- and post-Caledonian rocks will be presented on five 1:500 000 map sheets of which three are already published and a fourth is under compilation. The scientific results are documented in numerous publications both in international journals and in the Survey's own Bulletins and Reports. Review articles on various parts of the East Greenland Caledonian fold belt include those of Haller (1971), Henriksen & Higgins (1976), Higgins & Phillips (1979), Henriksen (1985, 1986), Hurst *et al.* (1985), Peel (1985), Peel & Sønderholm (1991), Higgins (1994) and Jepsen *et al.* (1994). Preliminary results of the 1997 and 1998 field work have been published in Survey reports (Higgins & Frederiksen 1998, 1999), and are summarised by Henriksen (1998) and in this article.

East Greenland Caledonides

The East Greenland Caledonian fold belt developed as a consequence of collision between the continents Laurentia (North America including Greenland) to the west and Baltica (North-West Europe) to the east following the closure of the Iapetus ocean in the late Ordovician – Silurian *c.* 440–400 million years ago. In Greenland the Caledonian fold belt developed along the eastern rim of the stable Precambrian Greenland shield and large regions are characterised by reworked Precambrian crystalline complexes overlain by Mesoproterozoic metasediments and Neoproterozoic to Lower Palaeozoic sedimentary successions. Throughout the length of the fold belt these diverse rock units were transported westwards as major thrust sheets and nappes with displacements of over 100 km, perhaps several hundred kilometres in places. The western border of the fold belt approximately follows the margin of the Inland Ice, along which a series of autochthonous to parautochthonous window complexes are intermittently exposed beneath the thrusts.

The occurrence of autochthonous to parautochthonous foreland windows along the west margin of the Caledonides implies that a wide zone along the west of the fold belt is essentially thin-skinned (Higgins & Leslie 1998); a thin-skinned deformation style is particularly well seen north of latitude *c.* 79°N where the transition from the main thrust front via a thin-skinned parautochthonous thrust belt to the autochthonous foreland is completely exposed. The rock units exposed in the northern parautochthonous windows have similarities with the foreland successions of eastern North Greenland. In the southern parautochthonous windows the units preserved differ markedly from the equivalent allochthonous successions in the fold belt to the east in that units equivalent to the Neoproterozoic Eleonore Bay Supergroup are absent in the windows and the Vendian and Palaeozoic successions in the windows are very much thinner than in the allochthon.

East of and structurally overlying the windows are major thrust units of intensely deformed polyorogenic gneiss complexes and their metasedimentary cover. These gneiss complexes dominate the East Greenland Caledonides and vary in character from region to region. Between *c.* 72°40´N and 81°N Palaeoproterozoic ortho-

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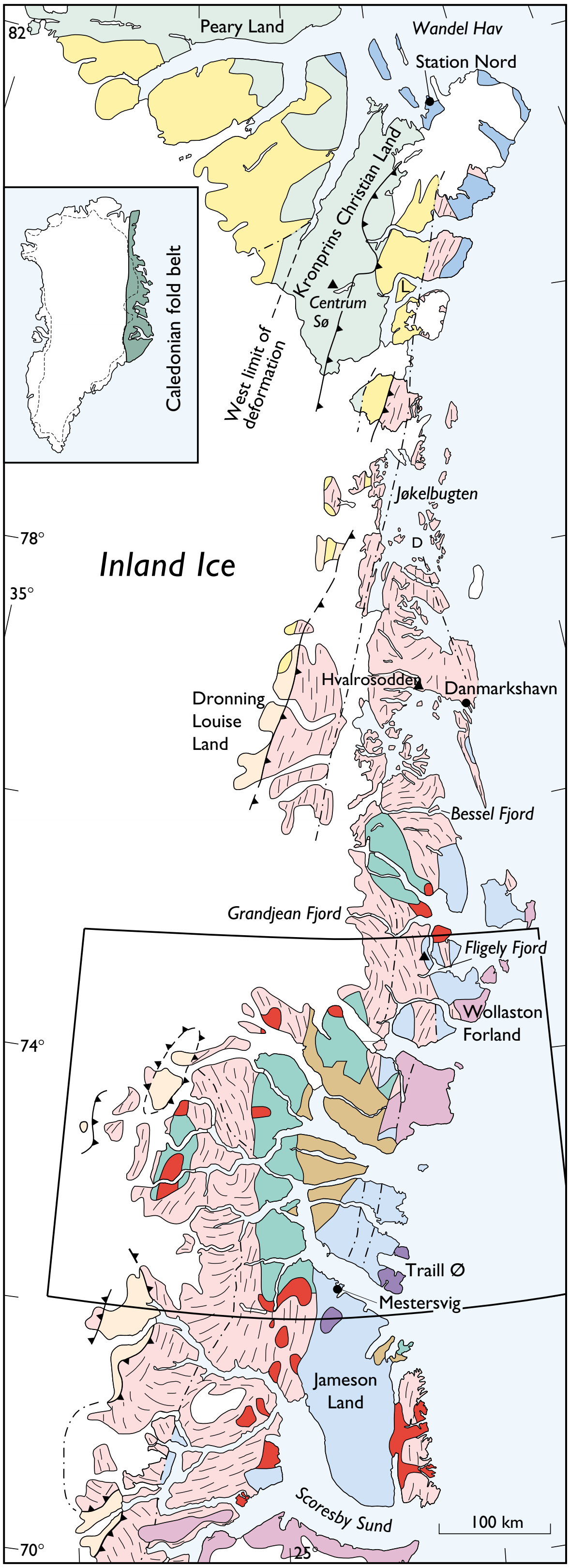

Fig. 1. Geological map of the East Greenland Caledonian fold belt with location of the 1:500 000 map: Kong Oscar Fjord (72°–75°N).

gneisses dominate, interpreted to have formed at the margin of an Archaean continent (Kalsbeek 1995). Exhumation of these gneiss complexes by thrusting during the Caledonian orogeny led to Caledonian deformation overprinting pre-existing deformation structures, and in some areas was accompanied by formation of Caledonian eclogites (Gilotti & Elvevold 1998). South of 72°40´N Archaean gneiss complexes prevail. In the southern half of the fold belt thick successions of Mesoproterozoic–Neoproterozoic metasediments structurally overlying the gneiss complexes are widespread.

Eastern parts of the southern half of the fold belt (*c.* 70°–76°N) have yielded isotopic evidence for Mesoproterozoic (Grenville) orogenic activity (950–1000 Ma). This activity included emplacement of a major suite of very coarse-grained granites as thick sheets and major bodies, and development of metamorphic overgrowths on detrital zircons in the Mesoproterozoic metasedimentary successions. Overlying these sequences in the central fjord zone of North-East Greenland are the thick successions of the Neoproterozoic Eleonore Bay Supergroup (14–15 km), Tillite Group (*c.* 1 km) and Cambro-Ordovician sediments (*c.* 3 km). The part of the fold belt preserving signs of Grenvillian activity (and the overlying sedimentary successions) may be confined to one or more major Caledonian thrust sheets. During the Caledonian orogeny the region affected by Grenvillian events was intensely reactivated, with widespread Caledonian migmatisation and granite emplacement. Distinction of Caledonian and Grenvillian deformation and plutonic events is a major problem in much of this region, which has only partially been resolved by isotopic studies. Both Grenville and Caledonian granites were apparently derived from melting of the same (or indistinguishable) Proterozoic metasedimentary rocks. Similarly the contact relationships of the Eleonore Bay Supergroup with underlying (older?) metasediments has provoked much discussion and intense study; in some areas the contact is an extensional fault, in other areas a thrust or shear zone.

Major westward and north-westward thrust displacements led to a piling up of nappes and thrust sheets to produce a major mountain chain, and it is known from the colour index of conodonts extracted from Ordovician sequences in the foreland windows that the overlying thrust pile reached thicknesses of 10–12 km (M.P. Smith and J.A. Rasmussen, personal communications 1999).

The field work in 1998 between latitudes 72°–75°N represents a re-investigation of areas extensively studied by geologists of Lauge Koch's expeditions (1926–58), whose results were published most notably in the compilations of Haller (1971) and Koch & Haller (1971) .

Field work organisation

The work in 1998 was a direct continuation of the field work in 1997 (Henriksen 1998) and based on the same basic logistic arrangements. The field investigations in 1998 were carried out during seven weeks between early July and late August with participation of a total

Fig. 2. Shifting of base equipment using a Twin Otter aircraft from a depot established in 1997 in the central part of Andrée Land.

of 43 persons including 29 geologists and ten student assistants (Henriksen 1999). The work was supported by two helicopters and a small, fixed wing Twin Otter aircraft (Fig. 2) which operated from Mestersvig, a former airport which is kept open for limited special operations by the military sledge patrol Sirius. The Survey group benefited substantially once again from base facilities at Mestersvig, organised and manned by the Danish Polar Center (DPC). Transport between Denmark and Mestersvig was carried out by the Swedish Air Force using a C-130 Hercules aircraft. As well as from Mestersvig, the helicopters operated during the season from a small unmanned satellite base established at Krumme Langsø 200 km to the north of Mestersvig.

In addition to the field teams working in the Caledonian fold belt the field party included three two-person Survey teams engaged in sedimentological studies in the post-Caledonian Upper Palaeozoic – Mesozoic successions, three Survey teams working with mineral prospecting and two teams from SAGA Petroleum working in co-operation with the Survey sedimentologists. Support was also given to a team from the Danish Lithosphere Centre (DLC) studying the Tertiary volcanic rocks of the nunatak region, and a group of four from the University Museum of Zoology, Cambridge, UK, engaged in palaeontological studies of vertebrate remains in Devonian sediments. During the season the Survey groups also co-operated with geologists from Oslo University, Norway and Massachusetts Institute of Technology (MIT), USA, who were investigating extensional structures and other late Caledonian features related to the formation of the Devonian–Carboniferous sedimentary basins.

Regional geological studies between 72°–75°N

The 1998 field work in the Caledonian fold belt supplemented the results from 1997 (Henriksen 1998), and was expanded northwards to cover the ground between latitudes 74° and 75°N. The terrain in the whole of the mapping region is characterised by rugged topography with mountains reaching almost 3000 m and dissected by wide fjords and glacial valleys, and with numerous local ice caps and glaciers. The main projects in 1998 included:

1. Pre-Caledonian basement in the crystalline complexes – a study using isotopic age determinations;
2. Structure and lithostratigraphy of the crystalline complexes;
3. Metamorphic studies of the infracrustal and supracrustal units;
4. Migmatisation processes and mechanisms, with studies of partial melting and emplacement patterns;
5. Sedimentology, lithostratigraphy and basin analytical studies of the Neoproterozoic Nathorst Land Group (Eleonore Bay Supergroup);
6. Sedimentology and basin analytical studies of the carbonate sediments in the Neoproterozoic Andrée Land Group (Eleonore Bay Supergroup);
7. Mineral resource investigations and follow-up of already located mineralisation sites and anomalies – especially those related to late Caledonian fault systems.

Preliminary results of the field work have been summarised by the participating geoscientists in a volume in the Survey's Rapport series (Higgins & Frederiksen 1999) which forms the basis of the following presentation.

Crystalline basement complexes

The Caledonian fold belt in the region mapped (72°–75°N) includes elements of at least four cycles of plate tectonic activity spanning from Archaean through Palaeoproterozoic and Mesoproterozoic to Caledonian time. The pre-Caledonian basement complexes are overlain by an up to 18–19 km thick succession of Neoproterozoic–Ordovician shallow-water sediments which are preserved as a low grade to non-metamorphic cover sequence and form part of a major Caledonian thrust complex. Caledonian granites are particularly concentrated in the contact zone between the Neoproterozoic sediments and the basement complexes.

The oldest, late Archaean, part of the basement complex lies in the southern part of the mapped region (Fig. 3). This extends southwards into the Scoresby Sund region (Henriksen 1986), where it is described as the Flyverfjord infracrustal complex. The characteristic rock types are amphibolite-banded orthogneisses with abundant ultrabasic lenses and cross-cutting amphibolitic basic dykes; Archaean ages of *c.* 3000–2600 Ma have been obtained from major orthogneiss units (Steiger *et al.* 1979; Rex & Gledhill 1981). During the present investigations this complex has been traced northwards to *c.* 72°40´N in Gletscherland (Thrane & Friderichsen 1999) and its Archaean age has been confirmed by a number of SHRIMP age determinations (F. Kalsbeek

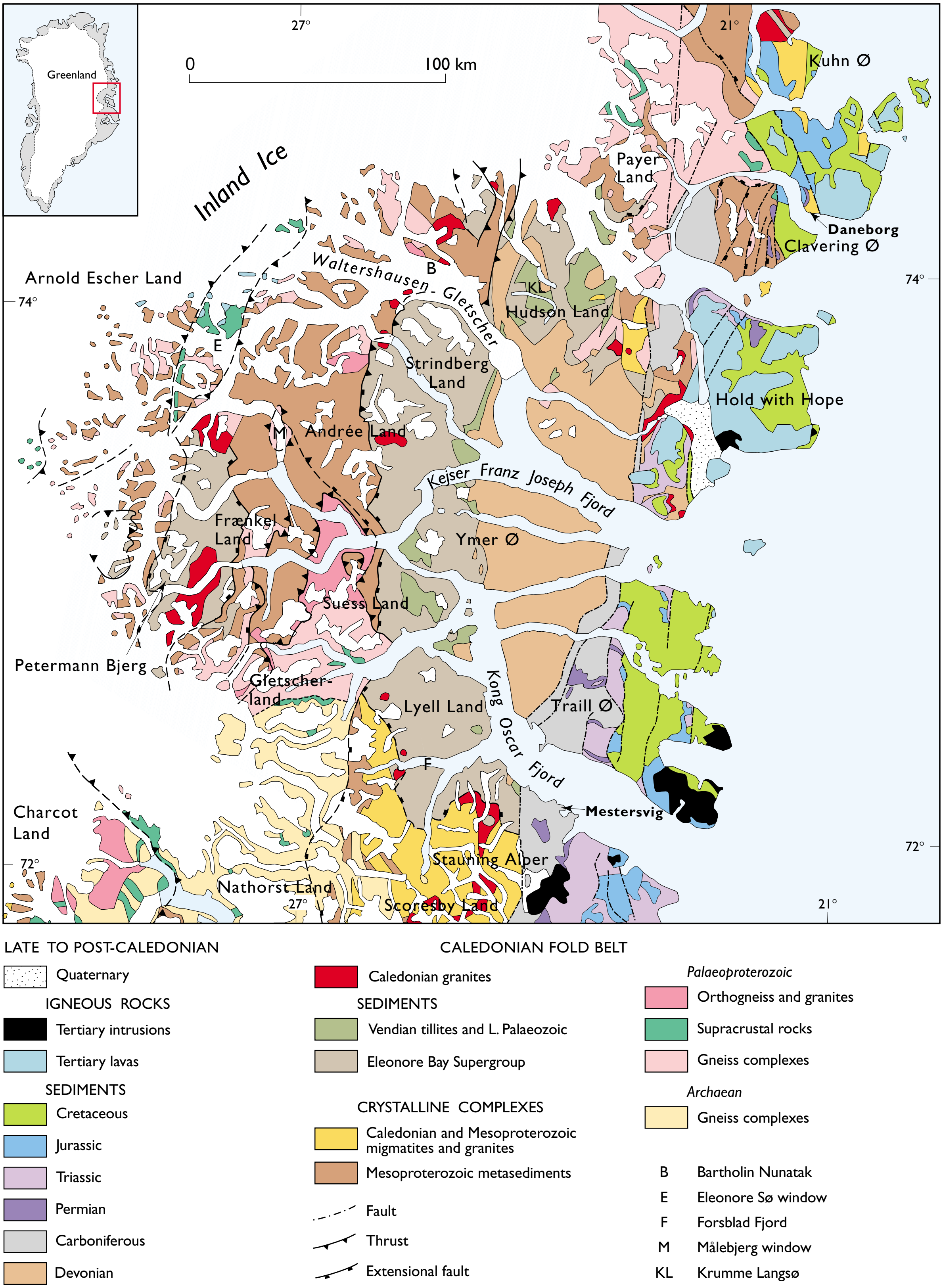

Fig. 3. Geological map of the Kong Oscar Fjord region, North-East Greenland.

and K. Thrane, personal communications 1999). A boundary between the Archaean complex and the Palaeoproterozoic gneiss complex to the north could not be established on field criteria alone, but its approximate position will probably be clarified by ongoing isotopic Rb/Sr model age studies and SHRIMP U–Pb zircon analyses.

The Palaeoproterozoic basement complexes north of 72°40´N comprise mainly grey gneisses with thin layers of supracrustal rocks and metamorphosed granitoid rocks. They represent remnants of a Palaeoproterozoic collisional orogen formed near the margin of an Archaean continent, and continue westwards and north-westwards to make up a major part of the Precambrian Greenland shield (Kalsbeek 1995). In the East Greenland Caledonides the Palaeoproterozoic basement complexes continue northwards to *c.* 80°N, and isotopic studies have revealed a spread of ages between *c.* 2000 and 1740 Ma (Kalsbeek *et al.* 1993); these imply that the orogenic cycles responsible for their formation extended over a period of *c.* 250 Ma. Within the study area of the present project (72°–75°N) new SHRIMP isotopic ages on zircons have yielded ages in the range 2000–1900 Ma (F. Kalsbeek and K. Thrane, personal communications 1999).

Evidence for a Mesoproterozoic (Grenvillian) event was previously documented by age determinations from both south and north of the present mapping area (Steiger *et al.* 1979; Strachan *et al.* 1995). It was therefore a particular aim of the present project to verify the extent of Grenvillian events in the area between 72° and 75°N. The results of these investigations now clearly show the existence of both a high-grade metamorphic event and formation of anatectic granites at around 930 Ma (Fig. 4; Thrane *et al.* 1999; Kalsbeek *et al.* in press). Mesoproterozoic metasediments are widespread, and are referred to as the Krummedal supracrustal sequence; they comprise a several kilometres thick cover sequence dominated by arenaceous and argillaceous lithologies, now folded together with its gneissic basement. Analyses of detrital zircons from the Krummedal sequence indicate that the sediments were deposited *c.* 1100–1200 Ma ago. The range of ages of the detrital zircons present do not match with the ages of the underlying crystalline basement, and must be derived from younger unknown source areas (Kalsbeek *et al.* in press). It is still an open question whether the Grenvillian events in this region relate to an orogeny or to an event of rifting and crustal thinning at around 1000–930 Ma.

Fig. 4. Foliated augen granite from Bartholin Nunatak giving an U–Pb zircon age of 934 ± 9 Ma (Grenvillian). Age determination by K. Thrane in Kalsbeek *et al.* in press. Photo: K. Thrane.

Neoproterozoic – Lower Palaeozoic sediments

Subsequent to the Mesoproterozoic (Grenvillian) events a thick succession of Neoproterozoic–Ordovician shallow-water sediments, with a composite thickness of up to *c.* 18–19 km, was laid down. The Precambrian part of the succession includes the up to 14–15 km thick Eleonore Bay Supergroup (EBS), dominated by siliciclastics in the lower part (Smith & Robertson 1999a) and with an upper part of sandstones, mudstones and carbonates (Sønderholm & Tirsgaard 1993; Frederiksen *et al.* 1999a). The EBS is overlain by the Vendian Tillite Group, in turn overlain by Cambro-Ordovician carbonates which contain a diversified shelf-type Pacific fauna indicative of an original position on the west side of the Iapetus ocean (Peel & Cowie 1979; Peel 1982).

Fig. 5. Succession in part of the Neoproterozoic Nathorst Land Group (Eleonore Bay Supergroup) at the type locality; west side of Alpefjord. The section is *c.* 800 m high.

Conodonts from the youngest sediments in the succession belong to the Llandeillian stage of the uppermost part of the Middle Ordovician (Peel 1985; Smith & Bjerreskov 1994), corresponding to an age of 462–465 Ma. Deposition of the entire sedimentary succession from early in the Neoproterozoic to Middle Ordovician spans a time interval over 400 Ma. The succession is ensialic and comprises shallow marine deposits throughout, implying that sedimentation and subsidence rates were roughly equal. The absence of angular unconformities in the Lower Palaeozoic reflects a non-tectonic environment during this part of the deposition. Opening of the Iapetus ocean is generally envisaged to have commenced in the latest part of the Neoproterozoic, but in Greenland there are no direct indications of the initiation of this event; no volcanic rocks are known, suggesting that the continent–ocean boundary must have been situated some distance to the east.

Prior to the 1998 field season the lowest division of the Eleonore Bay Supergroup was only known from investigations by members of Lauge Koch's expeditions (e.g. Fränkl 1953; Haller 1971) and limited Survey studies in the 1970s (Caby 1976). There was therefore a great need for a modern lithostratigraphical and basin analysis of this important clastic sedimentary succession. The lowest levels of the Eleonore Bay Supergroup are now known as the Nathorst Land Group (Sønderholm & Tirsgaard 1993). Investigations in 1998 (Smith & Robertson 1999a) established a lithostratigraphical division of the Nathorst Land Group into seven formations (NLG1–NLG7) with a total thickness of 9 km in the type area around Forsblad Fjord (Figs 3, 5). The lower boundary is nowhere preserved in an intact, unaltered condition; the lowest preserved levels are metamorphosed at medium to high grade, and the contact against the crystalline complexes is either an extensional fault or a shear zone. The upper boundary is conformable with the overlying Lyell Land Group in the south (Sønderholm & Tirsgaard 1993). However, in Andrée Land in the north, 2.5–3 km of the Nathorst Land Group were eroded away prior to the deposition of the Lyell Land Group, producing a hitherto unsuspected angular unconformity (Smith & Robertson 1999a). The Nathorst Land Group is dominated by sandstone and heterolithic mudstone and sandstone. One formation (NLG5), only present in the south, is a characteristic silty limestone band. Cross-bedding, wavy bedding and ripple lamination are common throughout; the depositional environment is interpreted as shelf to shoreface. The age of deposition is between about 920 Ma and Sturtian (*c.* 700 Ma).

The Petermann Bjerg Group in western Frænkel Land, west of the main outcrop area, is partly equivalent to the Nathorst Land Group. Mapping by Escher & Jones (1998) had strongly suggested a close similarity in development, and Smith & Robertson (1999a) established a correlation between the two successions, showing that the lower Petermann Bjerg Group is probably correlatable with formation NLG3 of the Nathorst Land Group and that the uppermost part of the Petermann Bjerg Group correlates with the lowest part of the Lyell Land Group.

Detailed sedimentological studies of the Andrée Land Group, the uppermost part of the Eleonore Bay Supergroup, were continued in 1998 (Frederiksen & Craig 1998; Frederiksen *et al.* 1999a). In 1998 a further 11 detailed profiles through the group were measured, and data now cover a belt of exposures extending for more than 250 km from north to south. The Andrée Land Group comprises limestones, dolomites and shales. It was divided into seven informal formations, AL1–AL7 by Sønderholm & Thirsgaard (1993) with a total thickness of *c.* 1200 m. The succession was mainly deposited in a marine shallow-water carbonate ramp environment with stromatolitic back ramp lagoon sediments, oolitic/pisolitic inner shallow shoal/barrier complex sediments, tidal channel breccias and conglomerates, and mid- to outer deep ramp storm-induced sediments (Frederiksen & Craig 1998). Deeper water marine slope environments represented by distal turbidites occur only in formation AL6. Evidence from the Andrée Land Group indicates an approximately east–west trend for the shoreline, which is in contrast to the north–south orientation with eastward dip of the shelf proposed from studies of the underlying Lyell Land Group (Tirsgaard & Sønderholm 1997) and Ymer Ø Group (Tirsgaard 1996).

The Andrée Land Group includes several thick dolomitic units, and a study of their diagenesis was included in the 1998 field work (Frederiksen *et al.* 1999b). At least two generations of dolomitisation are recorded, an early regional stratiform type, and a later cross-cutting type associated with minor faults and folds.

Caledonian orogeny: structures and metamorphism

The collision of Laurentia and Baltica which gave rise to the Caledonian orogen took place after the latest deposition on the continental margin *c.* 460 Ma ago. Emplacement of the widespread late orogenic granites *c.* 430 Ma ago may, however, be related to the late extensional phase of the orogen rather than the major compressional events which resulted in possibly several hundred kilometres of westwards thrusting. The continental collision and crustal thickening which affected East Greenland are thus of uppermost Ordovician to lowermost Silurian age, while subsequent exhumation and crustal thinning are of Late Silurian to Middle Devonian age.

One of the most significant results of the new field work in the region 72°–75°N in East Greenland has been the confirmation of the existence of major nappes and thrust sheets which have transported both crystalline basement and metasedimentary cover units westwards across the Precambrian shield that forms the Caledonian foreland to the west of the fold belt. Evidence of significant displacement is seen in the occurrence of major tectonic windows below Caledonian thrusts in the innermost fjord zone and the nunatak zone; thin Neoproterozoic – Lower Palaeozoic successions occur below major thrust complexes of higher grade infracrustal and supracrustal units (Leslie & Higgins 1998, 1999; Escher & Jones 1999; Smith & Robertson 1999b). Within the Målebjerg window the Vendian–Ordovician succession totals 206 m (Smith & Robertson 1999b) whereas the equivalent succession in the allochthonous areas of the fjord region totals 5–5.5 km; furthermore, the 14–15 km of the Eleonore Bay Supergroup at the base of the allochthonous succession in the fjord region are not represented in the foreland windows. Smith & Robertson (1999a, b) point out that as 20 km of sediment deposited in a predominantly non-rift setting, wedge out in a fraction of the width of the orogen, then the orogenic shortening due to thrusting must be substantial.

The Eleonore Sø window in the nunatak region is the largest of the tectonic windows in the study area, extending for over 100 km in a NNE–SSW direction (Leslie & Higgins 1998, 1999). It outcrops beneath a broad arched roof thrust which transports kyanite-grade metasediments, in places with granite veins, towards the north-west. The window exposes three distinct rock successions. A *c.* 1800 Ma old gneiss and granite basement is overlain by the Palaeoproterozoic Eleonore Sø supracrustal complex of pillow lavas, tuffs, gabbroic intrusions and various sediments, which in turn is unconformably overlain by a thin sequence of Cambro-Ordovician sediments. The Eleonore Sø complex is probably equivalent to the Charcot Land supracrustal sequence described from a similar tectonic window in the north-west part of the Scoresby Sund region (Steck 1971). The thin Lower Palaeozoic succession in the Eleonore Sø window comprises a *c.* 200 m thick quartzite unit with *in situ Skolithos* trace fossils indicative of a lowest Cambrian age, and an overlying 0–50 m thick carbonate succession of presumed Ordovician age (cf. Fig. 6).

One of the most difficult problems in relation to the structural interpretation of the fold belt is distinction between Caledonian and pre-Caledonian deformation and fold patterns in the crystalline complexes. It has not so far been possible to establish valid field criteria for distinguishing the Archaean, Palaeoproterozoic and Mesoproterozoic deformation phases from the later Caledonian deformation. However, most geologists have interpreted the dominant deformation seen in the metasedimentary successions as Caledonian. Thus Leslie & Higgins (1998) distinguished three phases of Caledonian compressional deformation in northern Andrée

Fig. 6. View of Målebjerg in western Andrée Land (see Fig. 3) showing part of the Målebjerg tectonic window. Grey gneisses beside the glacier are overlain by a prominent yellow-white to orange coloured quartzite 143 m thick which contains *Skolithos* trace fossils at several levels. A thin grey carbonate of probable Ordovician age occurs above the quartzite and immediately below a prominent flat-lying thrust, about half-way up the mountain in the field of view. The dark grey succession above the thrust comprises Proterozoic metasedimentary rocks of the Krummedal supracrustal sequence. Målebjerg is 1873 m high, and the glacier surface is at about 300 m altitude. Photo: A.K. Higgins.

Land and the nunatak region. A more complex history of deformation is described in the Frænkel Land region by Escher & Jones (1999), with distinction of five Caledonian phases of deformation: (1) an early phase of crustal thickening, (2) an early phase of granite emplacement associated with crustal extension, (3) northwards-directed thrusting, (4) upright folding on N–S, orogen-parallel axes and (5) late Caledonian extension. The late extensional phase is seen throughout the region as top-down-to-the-east displacements on major structural lineaments (e.g. Andresen *et al.* 1998; Elvevold & Gilotti 1998; Escher & Jones 1999).

Within the Caledonian fold belt high-pressure granulite facies rocks are found in gneiss complexes in Payer Land (Elvevold *et al.* 1999), and retrogressed high granulite facies rocks are also preserved in the Gletscherland region (Elvevold & Gilotti 1998) and on Clavering Ø (Jones & Escher 1999). The overall metamorphic grade in the crystalline complexes reflects amphibolite facies metamorphism, but there are all variations from low grade to high grade in the metasedimentary successions. The metamorphic grade in the Eleonore Bay Supergroup ranges from amphibolite facies in the lowest levels to non-metamorphic in the upper parts and in the overlying Tillite Group and Lower Palaeozoic rocks.

Granites and migmatites

Migmatisation and granite formation is a prominent feature of the southern part of the Caledonian fold belt in East Greenland (70°–76°N), corresponding to the region in which Mesoproterozoic and Neoproterozoic metasediments are abundant. Field relationships indicate clearly that migmatitic development and granite generation are closely associated with high-grade metasediments. The numerous granite sheets in the Mesoproterozoic Krummedal supracrustal sequence are anatectic and of

Fig. 7. Caledonian granite dykes and sheets intruding metasediments of the Nathorst Land Group (lowermost part of Eleonore Bay Supergroup). North side of outer Forsblad Fjord (see Fig. 3).

two distinct age groups; some are *c.* 930 Ma old (Grenville) and others are *c.* 430 Ma old (Caledonian) (Kalsbeek *et al.* in press). It is not generally possible to distinguish the two age groups either on field criteria or petrologically, except for those that penetrate into the lower parts of the Eleonore Bay Supergroup which must be Caledonian (Fig. 7). The granites in the region from 72° to 76°N are all interpreted as of low-temperature S-type, typically related to extensional tectonics (Kalsbeek *et al.* in press); they do not appear to be derived from deep-seated sources related to continental collision and subduction of crustal material.

Migmatites and Caledonian granites are the dominant rock units in the Stauning Alper region at about 72°N. In this region both metasediments of the Nathorst Land Group (Eleonore Bay Supergroup) and the Mesoproterozoic Krummedal supracrustal sequence are invaded by sheets of granitic material. Some of the granites which invade the Nathorst Land Group are cross-cutting and were originally described as post-tectonic, whereas others which are deformed were considered as synkinematic and thus older. However, Watt & Friderichsen (1999) consider both granite types to be of similar age, consistent with age dating results of 430–420 Ma for granite sheets and anatectic high grade neosome material in the migmatites. The difference between deformed and undeformed granitic material appears to reflect the structural environment in which they were formed. Above an intense deformation zone the granites are undeformed, while below this level they are deformed and associated with high-grade cordierite-sillimanite-garnet-bearing migmatitic metasediments.

Mineral resource investigations

Mineral resource investigations were integrated with the mapping in the crystalline areas and continued the work carried out in 1997 (Stendal & Wendorff 1998). Opportunity was also taken in the 1998 season to follow-up anomalies revealed by a transient electromagnetic and magnetic survey (AEM) carried out in 1997 (Thorning & Stemp 1998) that covered a region of over 5000 km^2 of the Mesozoic sedimentary basin in the northern part of Jameson Land (Fig. 1).

In the Caledonian fold belt and the adjacent areas with Devonian sediments investigations followed up earlier studies of mineralisation sites to obtain a better understanding of their size, character and occurrence in order to establish genetic models for their formation. The investigations were concentrated in the region between Kejser Franz Joseph Fjord and Clavering Ø, where post-Caledonian sediments are in fault contact with the underlying folded rock units. The region is characterised by the occurrence of a series of approximately N–S trending post-Devonian normal faults and lineaments, which have been exploited by various mineralisation types. The post-Devonian main fault system can be traced for a distance of more than 400 km. The mineralisations found in Caledonian crystalline complexes as well as post-Caledonian rocks are mostly of vein type and include base-metal mineralisations with pyrite, chalcopyrite, bornite and arsenopyrite (Stendal 1999). Gold anomalies previously detected by stream sediment analyses were also reinvestigated. A prominent rust zone in the crystalline complexes on southern

Clavering Ø has been known as a potential gold mineralisation since the beginning of the 1930s, when an exploratory 'mine' shaft was excavated. The area with this mineralisation was studied in detail, and rock, soil and stream sediment samples were collected for analytical and petrographic studies (Stendal *et al.* 1999b). The results of the field investigations indicate that the mineralisations are dominated by pyrite and arsenopyrite with quartz and fluorite in breccias. They are all related to fault zones.

The follow-up on the AEM survey in the Mesozoic basin in Jameson Land involved visiting 14 of the over 60 anomalies indicated by the survey (Stendal *et al.* 1999a). The anomalies are mainly associated with Tertiary sills intruded into Jurassic sandstones of the Kap Stewart Group (Dam & Surlyk 1998; Surlyk *et al.* in press). The most prominent type of mineralisation contained magnetite, pyrrhotite and pyrite with assessory chalcopyrite, ilmenite and galena.

Concluding remarks

With completion of the 1997–98 field mapping project, the entire length of the East Greenland Caledonian fold belt has now been mapped. Five map sheets at 1:500 000 cover the fold belt, the foreland areas in the west and the post-Caledonian basins in the east; three sheets are published, one is under compilation and field work for the final sheet is now complete. General regional overviews of the geology and the economic geological aspects of the region 72°–75°N have been obtained, and insights gained will help in understanding and interpreting other already mapped regions to the north and south. Laboratory investigations continue, and the results will be documented in Survey bulletins and maps and articles in international publications.

In addition to financing from Survey sources, some aspects of the project were based on funding from the Danish Natural Science Research Council and Carlsberg Foundation, the external sources funding mainly research in special topics concerning the pre-Caledonian basement terrain, Caledonian metamorphism, and studies of the Neoproterozoic carbonate sediments. With respect to the mineral exploration activities financial support was obtained from the Government of Greenland and the Danish Research Councils.

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New insights on the north-eastern part of the Ketilidian orogen in South-East Greenland

Adam A. Garde, John Grocott and *Ken J.W. McCaffrey*

During a five week period in August–September 1998 the poorly known north-eastern part of the Palaeoproterozoic (*c.* 1800 Ma) Ketilidian orogen between Kangerluluk and Mogens Heinesen Fjord in South-East Greenland (Fig. 1) was investigated in continuation of recent geological research in other parts of the orogen. The north-eastern part of the orogen is remote from inhabited areas. It is mountainous and comprises a wide nunatak zone which can only be reached easily by helicopter. Furthermore, access to coastal areas by boat is difficult because many parts of the coast are prone to be ice-bound even during the summer months, due to wind- and current-driven movements of the sea ice.

Transport was provided by a small helicopter (Hughes MD 500) on charter from Greenlandair, which allowed effective reconnaissance of large areas and identification of localities where detailed ground traverses could be carried out. The expedition was based at the abandoned

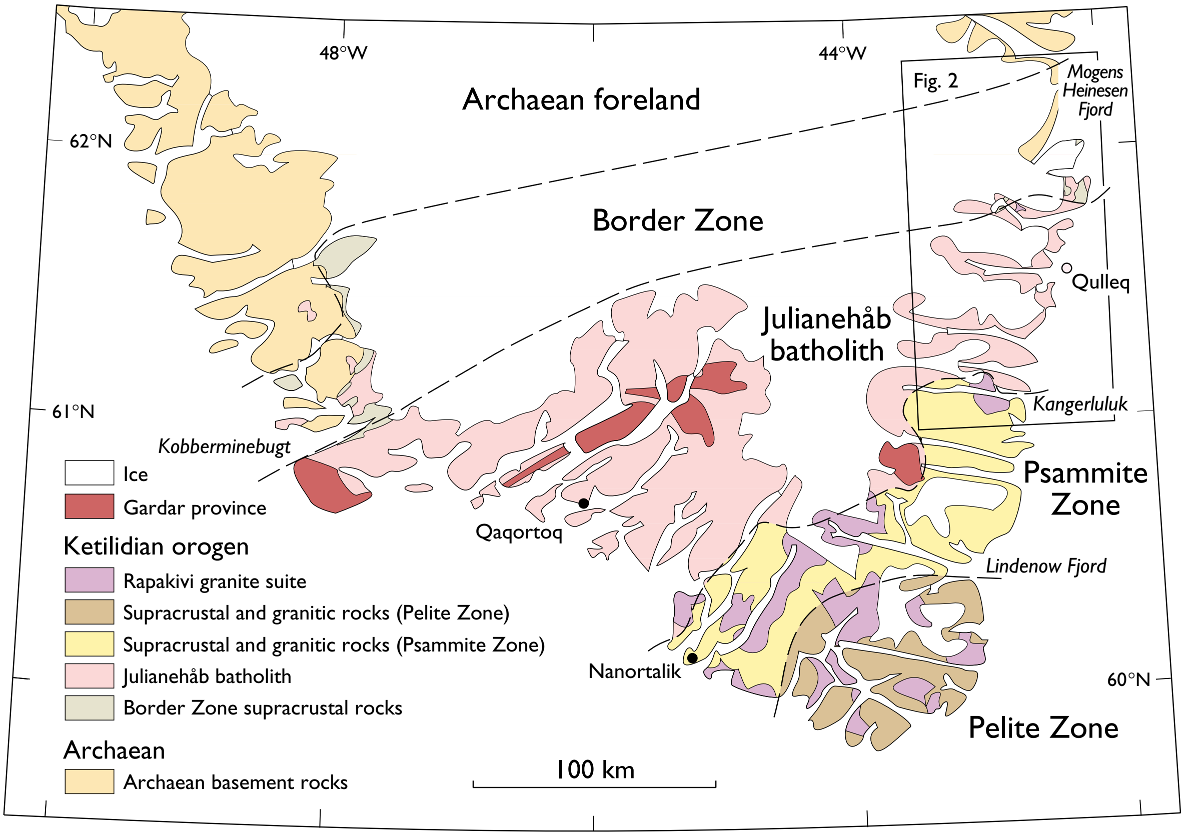
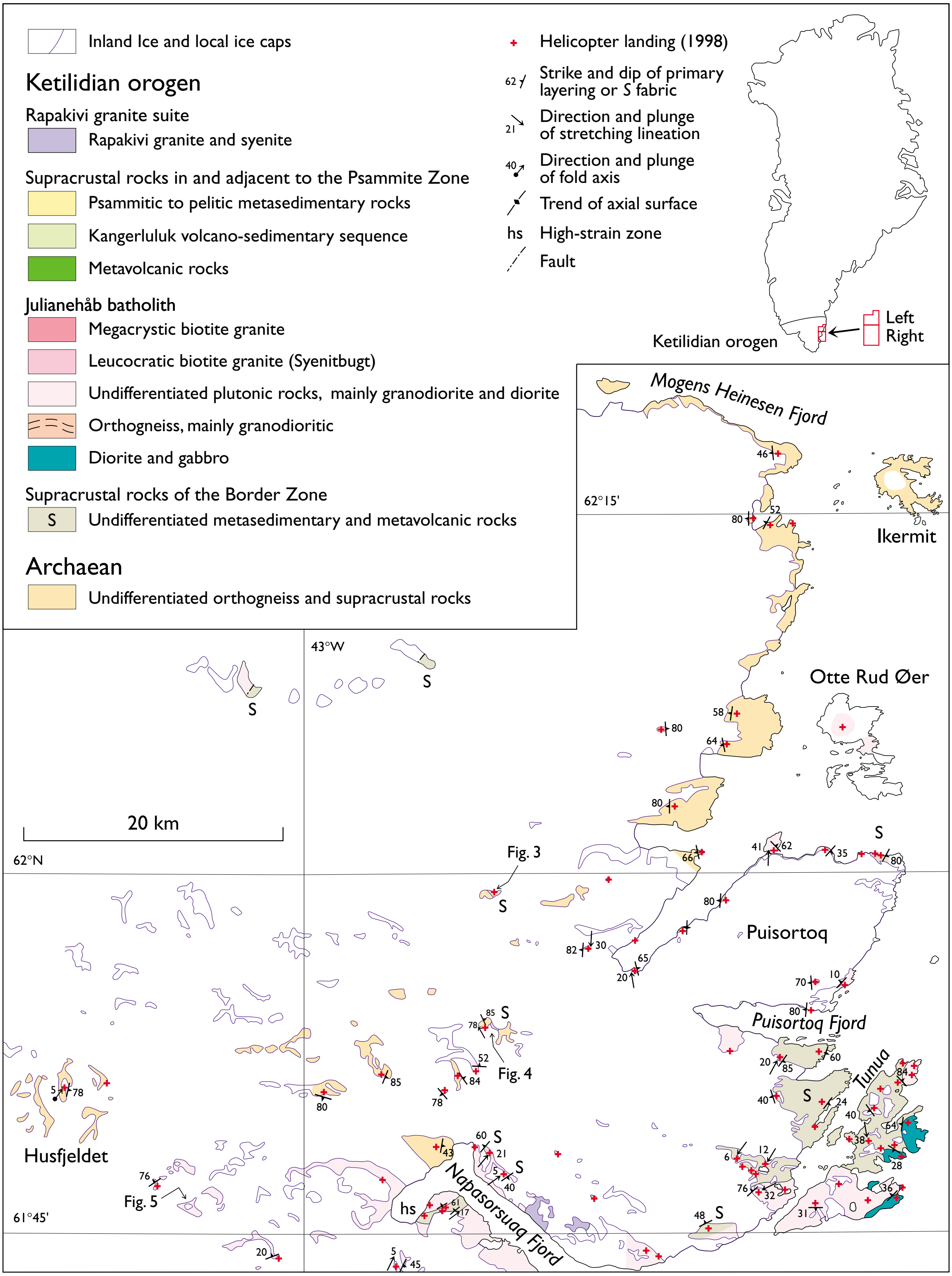


Fig. 1. The Ketilidian orogen in South Greenland, with the principal divisions according to Chadwick & Garde (1996). The frame indicates the location of Fig. 2, the region along the east coast covered by the investigation in 1998. An index map of Greenland is included in Fig. 2.


Inland Ice and local ice caps
Ketilidian orogen
Rapakivi granite suite
Rapakivi granite and syenite
Supracrustal rocks in and adjacent to the Psammite Zone
Psammitic to pelitic metasedimentary rocks
Kangerluluk volcano-sedimentary sequence
Metavolcanic rocks
Julianehåb batholith
Megacrystic biotite granite
Leucocratic biotite granite (Syenitbugt)
Undifferentiated plutonic rocks, mainly granodiorite and diorite
Orthogneiss, mainly granodioritic
Diorite and gabbro
Supracrustal rocks of the Border Zone
S Undifferentiated metasedimentary and metavolcanic rocks
Archaean
Undifferentiated orthogneiss and supracrustal rocks
Helicopter landing (1998)
62 Strike and dip of primary layering or S fabric
21 Direction and plunge of stretching lineation
40 Direction and plunge of fold axis
Trend of axial surface
hs High-strain zone
Fault
Ketilidian orogen
Left
Right
Mogens Heinesen Fjord
62°15'
Ikermit
Otte Rud Øer
43°W
20 km
62°N
Fig. 3
Puisortoq
Puisortoq Fjord
Tunua
Fig. 4
Husfjeldet
Fig. 5
hs
Napasorsuaq Fjord
61°45'
S

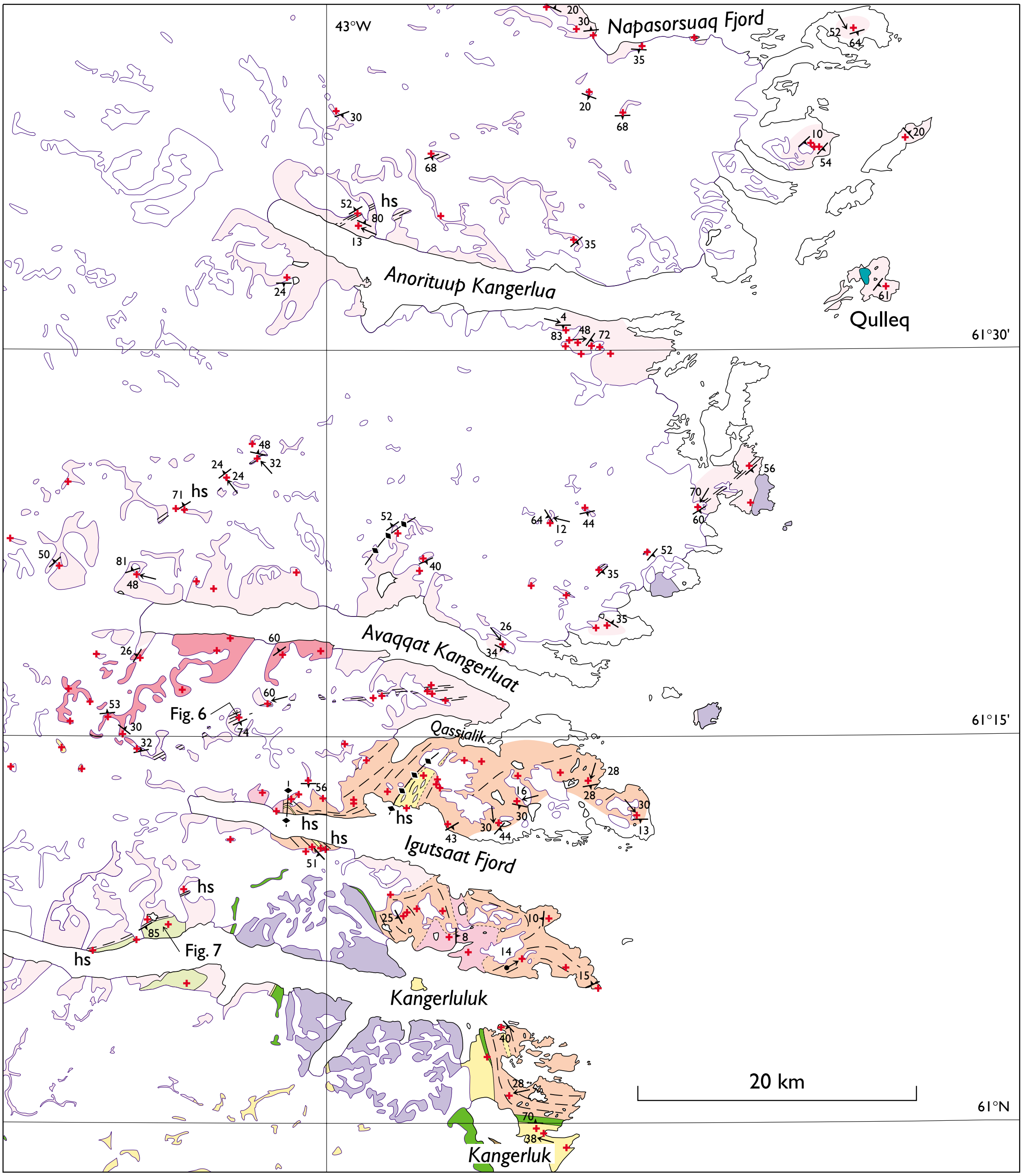


Fig. 2. **Left–right**. Geological sketch map of the north-eastern part of the Ketilidian orogen between Mogens Heinesen Fjord and Kangerluluk. The geological information is primarily based on observations made in 1998 (with helicopter landings shown by small red crosses), with a few additions in coastal areas based on an unpublished field map from 1970 by J.R. Andrews in the Survey's archives, and on personal communications with B. Chadwick and T.F.D. Nielsen in 1999. Nunataks and other areas lacking colour have not been visited. The area south of Kangerluluk was mapped in 1994 and 1996 (Garde *et al.* 1997). The positions of Figs 3–7 are shown with long arrows.

Loran station on the island of Qulleq (Figs 1, 2), and all observations were made during day trips with the helicopter. With a staff of just three geologists this proved to be a very effective way of using the limited field period and economic resources available for the project, and at the same time the amount of necessary field equipment was substantially reduced.

The principal aims of the 1998 field programme were: (1) to locate the north-eastern boundary of the Ketilidian orogen against the Archaean craton and study the nature of this boundary; (2) to study magmatic and tectonic accretion processes in the north-eastern part of the Julianehåb batholith which forms the central part of the orogen (see below); (3) to establish and correlate structural relationships in the batholith with those previously studied in the fore-arc basin to the south; (4) to study the nature and extent of a major mylonite zone which had previously been located at Igutsaat Fjord. Some 175 localities were visited (Fig. 2), many only briefly for reconnaissance purposes, but about half involved longer stops at which detailed observations were made or traverses carried out.

Previous work

On the basis of systematic investigations of the western and southern parts of the Ketilidian orogen in the 1950s and 1960s, Allaart (1976) divided the Ketilidian orogen into four different zones, which were revised by Chadwick & Garde (1996) into (1) the *Border Zone* of reworked Archaean basement and Ketilidian supracrustal rocks in the north-western part of the orogen, (2) the juvenile, calc-alkaline *Julianehåb batholith* in the central part, and (3–4) the *Psammite and Pelite Zones* in the south-east, consisting of deformed and metamorphosed supracrustal rocks largely derived by erosion of the Julianehåb batholith and interpreted as a fore-arc basin. A short updated outline of the orogen was published by Garde *et al.* (1998a), and Fig. 1 shows the fourfold division of the orogen.

Coastal areas in the north-eastern part of the Ketilidian orogen were visited by boat in 1970 (Andrews *et al.* 1971, 1973), when extensive areas of granitic rocks were observed and correlated with the Julianehåb batholith on the west coast of South Greenland. Extensive areas of leucocratic gneisses were also reported and interpreted as acid metavolcanic rocks. In 1987, low-grade sedimentary rocks of presumed Ketilidian age were discovered on nunataks west of Otte Rud Øer (Fig. 2 left; B. Chadwick and M. Rosing, personal communications 1995). In 1992, the first year of the Survey's SUPRASYD project (1992–1996), a stream sediment survey and a few days of geological reconnaissance were carried out by helicopter in the north-eastern part of the orogen (Chadwick 1992; Steenfelt *et al.* 1992; Nielsen *et al.* 1993). The field work in 1992 led to a re-interpretation of the previously reported acid metavolcanic rocks on the island of Ikermit (Fig. 2) as Archaean gneisses, reworked by intense deformation in a Ketilidian shear zone (Chadwick *et al.* 1994a), and it was considered that the existence of extensive areas of supracrustal rocks in the north-eastern part of the orogen previously reported by Andrews *et al.* (1971, 1973) was questionable. However, the more thorough study in 1998 firmly established the presence of a more than 5 km thick sequence of migmatised psammites to the north of Napasorsuaq Fjord (see below).

The north-eastern Border Zone

The north-eastern Border Zone is best addressed in the light of its well established counterpart on the west coast in the north-western part of the orogen (Fig. 1). The Border Zone in the north-west comprises Archaean basement rocks unconformably overlain by Ketilidian metasedimentary and basic metavolcanic rocks (the Vallen and Sortis Groups: Bondesen 1970; Higgins 1970), which become progressively involved in Ketilidian metamorphism and deformation towards the south (Henriksen 1969; Allaart 1976) and intruded by Ketilidian granites. It was firmly established during the 1998 field work that the north-eastern Border Zone, in South-East Greenland, is of a broadly similar nature. However, there is no equivalent to the metavolcanic Sortis Group and, in the short time available, we were unable to locate unequivocal exposures of any basal unconformity to the metasediments.

Archaean basement

The south-eastern boundary of the Archaean basement extends from north-west of Otte Rud Øer along the north-western side of Puisortoq and continues through the head of Napasorsuaq Fjord to the nunataks around Husfjeldet (Fig. 2). The basement largely consists of tonalitic orthogneiss with deformed and metamorphosed fragments of anorthosite, leucogabbro and gabbro, and numerous layers and lenses of supracrustal amphibolite and pelitic metasediment. The Archaean rocks contain a series of large N–S trending, upright, open to tight folds accompanied by a N–S tectonic fabric of variable intensity. The gneiss commonly has blebby textures characterised by clusters of secondary biotite or actinolitic hornblende, indicative of retrogression from granulite facies; relict hypersthene was found in basic lithologies north of the head of Napasorsuaq Fjord. According to previous observations by B. Chadwick (personal communication 1999), the retrogression took place in the Archaean, prior to or during the latest phase of deformation which produced the above mentioned upright folds. These structures are Archaean because they are cut by early Proterozoic (pre-Ketilidian) dolerite dykes.

Small intrusions of Ketilidian granite, diorite and gabbro, typically in the form of 5–100 m wide inclined sheets, are common together with dykes and low-angle sheets of appinite up to a few metres thick. Similar dykes have previously been observed in the Archaean foreland as far north as 63°N (Chadwick & Walton 1988; Chadwick & Garde 1996). Close to the Archaean basement some of the Ketilidian intrusive rocks contain N–S fabrics with steep internal strain gradients parallel to their margins. This indicates that localised Ketilidian reworking in these areas followed the Archaean N–S structural grain. Brown, undeformed, mostly E–W trending dolerite dykes of presumed Gardar age cut the Archaean and Ketilidian rocks. Some of the Gardar dykes contain conspicuous plagioclase megacrysts several centimetres across.

Low-grade Ketilidian supracrustal rocks overlying Archaean basement

Three new occurrences of low-grade Ketilidian metasedimentary rocks were discovered in the region underlain by Archaean basement, south and south-east of the previously visited exposures on nunataks *c.* 40 km west of Otte Rud Øer (Chadwick 1992). On the north face of nunatak 1120 m, 15 km south of the above mentioned nunataks and 20 km north of the head of Napasorsuaq Fjord (Fig. 2 left), an isolated sequence of shallowly NW-dipping conglomerate is present (Fig. 3). The sequence is more than 100 m thick and is in faulted contact with amphibolite and diorite, and cut by thin (*c.* 50 cm) Ketilidian diorite sheets. The cross-bedded and graded conglomerate beds are facing right way up and consist of up to cobble-sized clasts of vein quartz and granite, and dark, fine-grained clasts which are probably of sedimentary origin. The base of the conglomerate is not exposed. It may have been deposited

Fig. 3. Flat-lying Ketilidian conglomerate at base of nunatak 20 km north of the head of Napasorsuaq Fjord, within the region underlain by Archaean basement. Ken McCaffrey seen from the helicopter for scale. Position shown on Fig. 2.

Fig. 4. Flat-lying, fault-bounded Ketilidian sedimentary rocks at the base of nunatak 9 km north of the head of Napasorsuaq Fjord, within the region underlain by Archaean basement. The exposure is *c.* 50 m high. Location is shown on Fig. 2.

close to the Archaean–Proterozoic unconformity, and was faulted and intruded during subsequent Ketilidian events.

The second occurrence of low-grade Ketilidian supracrustal rocks was identified from the helicopter on the vertical south face of nunatak 1171 m, 9 km north of the head of Napasorsuaq Fjord (Fig. 2 left), where two fault-bounded blocks of flat-lying Ketilidian metasedimentary rocks occur (probably quartzite and semipelite, Fig. 4). The nearest landing spot some 100 m west of and below the cliff consists of migmatised Archaean orthogneiss with a distinct, vertical NNW-trending *S* fabric and a NNW-plunging stretching lineation, which we believe is of Archaean age.

The third occurrence is located on nunatak 1650 m, 9 km west-south-west of the head of Napasorsuaq Fjord, where a *c.* 5 m thick Gardar dyke emplaced into Ketilidian granites contains closely packed, angular xenoliths of low-grade Ketilidian psammite up to 20 cm across.

Deformed Ketilidian supracrustal rocks in the southern part of the Border Zone

South of the Archaean basement an up to *c.* 20 km wide zone occurs within which up to 5 km thick screens of generally highly deformed Ketilidian supracrustal rocks are embedded within intrusive members of the Julianehåb batholith. Arkosic and quartzitic, medium-grained psammitic rocks predominate, but thin horizons of polymict conglomerate, (semi)pelitic and metavolcanic rocks also occur. The rocks in this zone generally possess a NE–SW trending, steep to moderately NW-dipping tectonic fabric (*S1*), commonly combined with a subhorizontal stretching lineation. Sigmoidal feldspar porphyroclasts and other asymmetric kinematic indicators locally provide clear evidence of sinistral displacement. Between the outer parts of Napasorsuaq Fjord and Puisortoq Fjord, the steep *S1* fabric is deformed by recumbent minor folds and a weak to intense crenulation cleavage (*S2*) with subhorizontal or gently W-dipping axial planes. No related major structures have yet been identified. On the north coast of Puisortoq, on the island east of Tunua and north of inner Napasorsuaq Fjord (Fig. 2), the psammitic rocks are migmatised and in places partially melted to yield S-type granites. The partial melting indicates that some of the psammitic rocks have arkosic compositions, as in the Psammite Zone further south, where it has been shown that the detrital source of the metasediment was largely Ketilidian (Hamilton *et al.* 1996; Hamilton 1997; Garde *et al.* 1998a). An ion probe U–Pb age determination study of detrital zircon grains and their overgrowths from samples of migmatised psammite and S-type granite is in progress, and is expected to yield information with respect to the provenance of the detritus and the age of the Ketilidian thermal event.

Fig. 5. Nunatak 1480 m about 17 km west of the head of Napasorsuaq Fjord exposing granitic rocks of the Julianehåb batholith cut by flat-lying (Ketilidian) appinite sheets and a vertical Gardar dyke. The exposure is *c.* 200 m high. Position shown on Fig. 2.

Fig. 6. High-strain zone in the Julianehåb batholith: mylonitic Ketilidian orthogneiss cut by a thin, flat-lying granite sheet with a very weak *S* fabric (upper central part of the picture). Inner part of the peninsula between Avaqqat Kangerluat and Igutsaat Fjord (position shown on Fig. 2).

Julianehåb batholith

The Julianehåb batholith between Napasorsuaq Fjord and Kangerluluk (Figs 2, 5) largely consists of biotite (-hornblende) granite and granodiorite plutons and hornblende-bearing, less voluminous and more mafic lithologies. The survey of much of the batholith zone was of a reconnaissance nature, and the isolated exposures on nunataks and between glaciers made it difficult to identify and outline individual plutons in the short time available.

In contrast to the southern and north-western parts of the Julianehåb batholith, where steep magmatic and tectonic fabrics with subhorizontal stretching lineations and sinistral transpressive displacement patterns predominate (Chadwick *et al.* 1994b; Garde *et al.* 1998b; McCaffrey *et al.* 1998), we found considerable evidence in the north-eastern part of the batholith that many of its intrusive members were emplaced as moderately inclined sheets. The original magmatic fabrics are commonly retained, generally with orientations parallel to the margins of the intrusions, without overprinting by younger solid-state fabrics. Swarms of subhorizontal to gently inclined, undeformed appinite sheets are common in some parts of the batholith (Fig. 5) and reinforce the impression that the overall batholith structure is subhorizontal. In detail, however, some of the subhorizontal appinite sheets are discordant to the less obvious but moderately inclined intrusive sheeting of their host rocks and the magmatic layering within them.

As in other parts of the batholith, the magmatic fabrics have been overprinted by steep solid-state planar fabrics post-dating the magmatic emplacement in a number of NE–SW trending high-strain zones. These are spaced some 10–15 km apart from each other and are commonly cut by thin granite sheets with weak fabrics (Fig. 6), which indicate that the high-strain zones were developed before the magmatic activity completely ceased. U–Pb zircon dating of two discordant granite sheets and of a few large plutonic complexes within the batholith, is under way.

Stretching lineations in the high-strain zones have oblique plunges (most commonly to W or NW), which combined with reverse slip indicators show that a significant component of vertical displacement is present on some of the shear zones. It is possible that at least some of the high-strain zones in the batholith are synplutonic, and steeply plunging stretching fabrics may reflect elements of roof uplift or floor depression during emplacement of subhorizontal batholith components. Roof uplift during magmatic emplacement can only take place in the uppermost part of the crust, and if this emplacement mechanism was involved, it would therefore imply that a relatively high crustal level is exposed in this part of the batholith. However, independent supporting evidence for this, such as subvolcanic magmatic textures in the plutonic complexes, has not been found. Furthermore, at this stage of our investigation we are unable to readily distinguish between high-strain zones, which are related to emplacement mechanisms of individual batholith intrusions, and high-strain zones which are part of a regional deformation system.

Supracrustal enclaves, flat-lying tectonic fabrics and upright folds in the south-eastern part of the batholith

The south-eastern part of the Julianehåb batholith between outer Kangerluluk and Avaqqat Kangerluat (Fig. 2 right) largely consists of granitic (*s.l.*) orthogneisses with an intense flat-lying planar fabric, which at least locally reflects more than one phase of deformation. On both sides of Igutsaat Fjord the orthogneisses are interleaved tectonically with thinner screens (up to a few hundred metres thick) of intensely deformed psammitic paragneiss. The 1998 field work revealed that the mylonites found on the south and north coasts of inner Igutsaat Fjord during reconnaissance in 1994 and 1996 (Chadwick *et al.* 1997) represent a local intensification and re-orientation of the regional planar fabric. A screen of intensely deformed, predominately psammitic and semipelitic supracrustal rocks, up to almost 1 km thick and dilated by intrusive granite sheets, occurs within the orthogneisses south of Qassialik (Fig. 2 right, 61°15´N). Panels of supracrustal rocks up to two hundred metres thick have also been identified within the mylonites at Igutsaat Fjord. These supracrustal rocks are tentatively loosely correlated with the Psammite Zone to the south.

The flat-lying orthogneisses and their enclaves of supracrustal rocks have been folded by upright folds. The largest of these is an upright, tight antiform south of Qassialik, while another prominent antiform fold affects the mylonite north of Igutsaat Fjord (Chadwick *et al.* 1997). It is possible that both of these folds are contemporaneous with the NE–SW trending shear zones described in the foregoing section, but the structural relationships are complex and further discussion is beyond the scope of this short overview.

Structural and age correlation with the Psammite Zone

In order to correlate observations in 1998 from north of Kangerluluk with earlier work in the Psammite Zone to the south, a number of localities were visited along a traverse from the orthogneisses towards the south into the previously mapped northern part of the Psammite Zone between outer Kangerluluk and Kangerluk (Chadwick 1996). Our observations indicate that the intense foliation in the southern part of the Julianehåb batholith in South-East Greenland is continuous with the main planar fabric in the northern part of the Psammite Zone. In the metasedimentary rocks south of Kangerluluk, which were deposited on early batholith members and intruded by late batholith members, the main planar fabric is a composite *L-S* schistosity (*S1* + *S2*) resulting from transposition of bedding and a locally recognised first cleavage (*S1*) during an intense second deformation phase (Chadwick *et al.* 1997; Garde *et al.* 1997). Kinematic evidence suggests that the sense of shear is broadly parallel to the length of the orogen and consistent with that found in the Psammite Zone to the south, i.e. top to NE on shallow NE-plunging stretching lineations.

U–Pb zircon geochronology by Hamilton *et al.* (1996) and Hamilton (1997) helps to correlate the deformation events. Age determination of an orthogneiss east of Kangerluk yielded an age of 1845 ± 3 Ma (2σ confidence interval), and a statistically identical age (1846^{+2}_{-1} Ma) was obtained from a weakly deformed granodiorite at Kangerluluk. These results imply that the orthogneisses are part of the basement to the Psammite Zone, since most detrital zircon ages obtained from the metasedimentary rocks have younger ages. The age of the second deformation phase in the Psammite Zone has been determined as 1792 ± 1 Ma by dating of a synkinematic hornblende granite. A minimum age has also been obtained for the mylonite north of Igutsaat Fjord: a 2 m wide, NNE–SSW trending granite sheet which cuts the folded mylonite and is axial planar to the above mentioned antiform fold, yielded a U–Pb zircon age of 1794 ± 1 Ma. With support from the new observations around Igutsaat Fjord and Kangerluluk these age determinations imply that the *D1/D2* event in the Psammite Zone can probably be extended northward to north of Igutsaat Fjord. The deformation was either contemporaneous and took place at 1793 Ma (within error of the age determinations from each region), or it was diachronous and slightly earlier in the north.

Supracrustal rocks at the northern margin of the Psammite Zone

A well-preserved volcano-sedimentary sequence in low amphibolite facies, which unconformably overlies granodiorites of the Julianehåb batholith on the south coast of Kangerluluk, was briefly described by Stendal *et al.* (1997) and in more detail by Mueller *et al.* (in press). The supracrustal rocks were discovered during reconnaissance in 1994, early in the summer when much of the region was still covered by snow. In 1998, when the snow cover was at its minimum in late August, it was found that a higher stratigraphic level of the same volcano-sedimentary sequence is well exposed on the north coast of Kangerluluk (Fig. 2), but the short time available only allowed a very cursory investigation.

The internal structure consists of alternating zones of low deformation with moderate northerly dips, and more intensely deformed zones with steep NW dips. The lower exposures on terraces and slopes dropping off towards the fjord appear from the air to consist of deformed pillow breccia, which is also the dominant lithology in the southern part of the plateau *c.* 400 m above sea level, where cuspate bottoms of intact pillows show that the sequence is younging upwards. Plagioclase-phyric mafic dykes and zones of fine-grained, intermediate to basic sills or flows a few metres thick were also observed, and common zones of intense epidote alteration resemble those described from south of the fjord. The pillow breccia is overlain by several hundred metres of clast-supported conglomerate beds with boulders of fine-grained, dark, porphyritic basaltic rocks and smaller clasts of fine-grained felsic rocks (Fig. 7), interleaved with few metres thick, ?tuffaceous horizons with numerous small basaltic rock fragments and weathered-out vugs. The upper part of the sequence is dominated by plane-bedded and trough cross-bedded, dark grey psammitic rocks with primary load structures formed by liquefaction of wet sediment; these rocks are likely to have been formed by redeposition of volcanic material. The uppermost exposures are intruded by undeformed, homogeneous, medium-grained granitic sills of batholith affinity.

The volcano-sedimentary rocks exposed on the south side of Kangerluluk host a high-grade gold mineralisation in a rusty-weathering alteration zone with vein quartz and copper sulphides (Stendal 1997). During the short visit to the north coast of Kangerluluk no major alteration zones of this kind were encountered, but local rust-weathering was observed in the pillow breccias and volcanogenic conglomerates, and the area is considered to have potential for gold mineralisation.

Fig. 7. Undeformed, polymict conglomerate with large volcanic boulders in the northern part of the Kangerluluk volcano-sedimentary sequence. Hammer, 45 cm long, for scale. North of central Kangerluluk, position shown on Fig. 2.

Conclusions

The short and relatively inexpensive expedition to the north-eastern part of the Ketilidian orogen described above has firmly established for the first time that the north-eastern Border Zone of the orogen, like the north-western Border Zone, comprises Archaean basement unconformably overlain by extensive Ketilidian supracrustal rocks, progressively reworked towards the south and intruded by Ketilidian igneous rocks dominated by granites (*s.l.*), diorites and appinites. There is, however, no equivalent of the basic metavolcanic Sortis Group found in the north-west.

In contrast to the southern and north-western parts of the Julianehåb batholith, where steep magmatic and tectonic fabrics with subhorizontal stretching lineations and sinistral displacement patterns predominate, many of the plutons in the north-eastern part of the batholith were emplaced as moderately inclined sheets. As elsewhere in the batholith, several late- to post-magmatic, NE–SW trending high-strain zones were identified, but their stretching lineations have oblique plunges and there is evidence of reverse slip.

In the south-eastern part of the batholith, a regional flat-lying tectonic fabric is provisionally concluded to be structurally contiguous with mylonites at Igutsaat Fjord and with the previously established *S1/S2* fabric in the Psammite Zone to the south. There are also younger upright folds. Existing U–Pb zircon age data suggest that the intense deformation took place relatively late in the magmatic and tectonic accretion of the batholith.

A relatively well-preserved continuation of the Kangerluluk volcano-sedimentary succession, previously described from the south coast of Kangerluluk, was found north of the fjord and presents a new potential target for gold exploration.

Acknowledgements

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Airborne geophysical surveys in Greenland in 1998

Thorkild M. Rasmussen and *Leif Thorning*

Airborne geophysical surveying in Greenland during 1998 consisted of a magnetic project referred to as 'Aeromag 1998' and a combined electromagnetic and magnetic project referred to as 'AEM Greenland 1998'. The Government of Greenland financed both with administration managed by the Geological Survey of Denmark and Greenland (GEUS). With the completion of the two projects, approximately 305 000 line km of regional high-resolution magnetic data and approximately 75 000 line km of detailed multiparameter data (electromagnetic, magnetic and partly radiometric) are now available from government financed projects. Figure 1 shows the location of the surveyed areas with high-resolution geophysical data together with the area selected for a magnetic survey in 1999. Completion of the two projects was marked by the release of data on 1 March, 1999. The data are included in the geoscientific databases at the Survey for public use; digital data and maps may be purchased from the Survey.

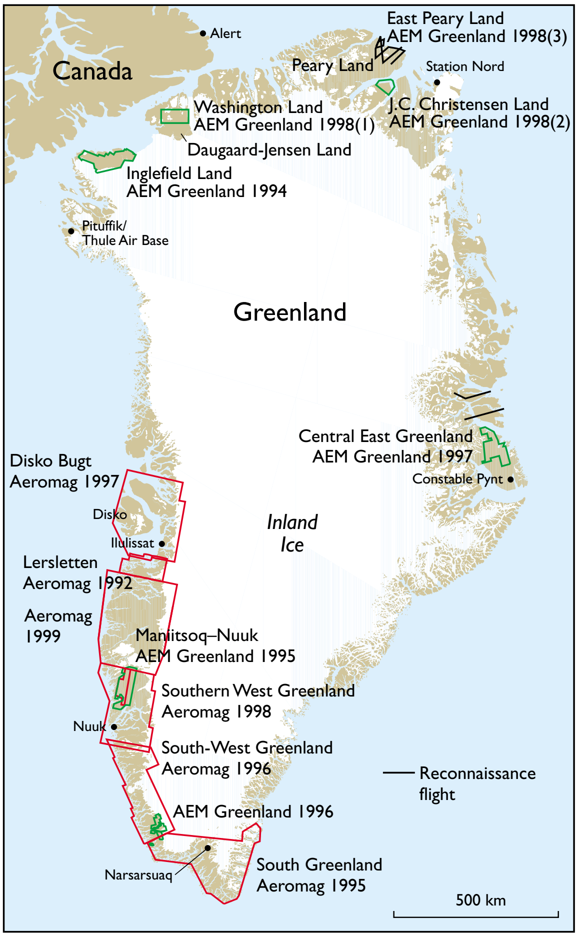

Fig. 1. Locations of high-resolution airborne geophysical surveys carried out in Greenland in the period 1992–1998, and the planned Aeromag 1999 survey in West Greenland.

The combined electromagnetic and magnetic survey in 1998 completes the five-year project AEM Greenland 1994–1998 that has had the primary objective of stimulating mining exploration activity in Greenland (Stemp & Thorning 1995). During this five-year period, high-resolution electromagnetic and magnetic data have been acquired from selected areas in Greenland (Fig. 1). The surveys cover regions of contrasting topography and geology from the Archaean craton to basalts of the Tertiary igneous province. A complete reference list including publications from the previous surveys is found in Thorning & Stemp (1998).

Contractors for the two projects were selected under EU open tender procedures in 1997, which included options for extending the projects in 1997 to 1998.

Aeromag 1998

Approximately 71 000 line km of total field magnetic data were acquired in southern West Greenland in the region indicated in Figs 1 and 2. The survey block covers part of the Archaean craton between 63°40´N and 65°45´N, ranging from the permanent ice of the Inland Ice to the Davis Strait. In the northern half of this region,

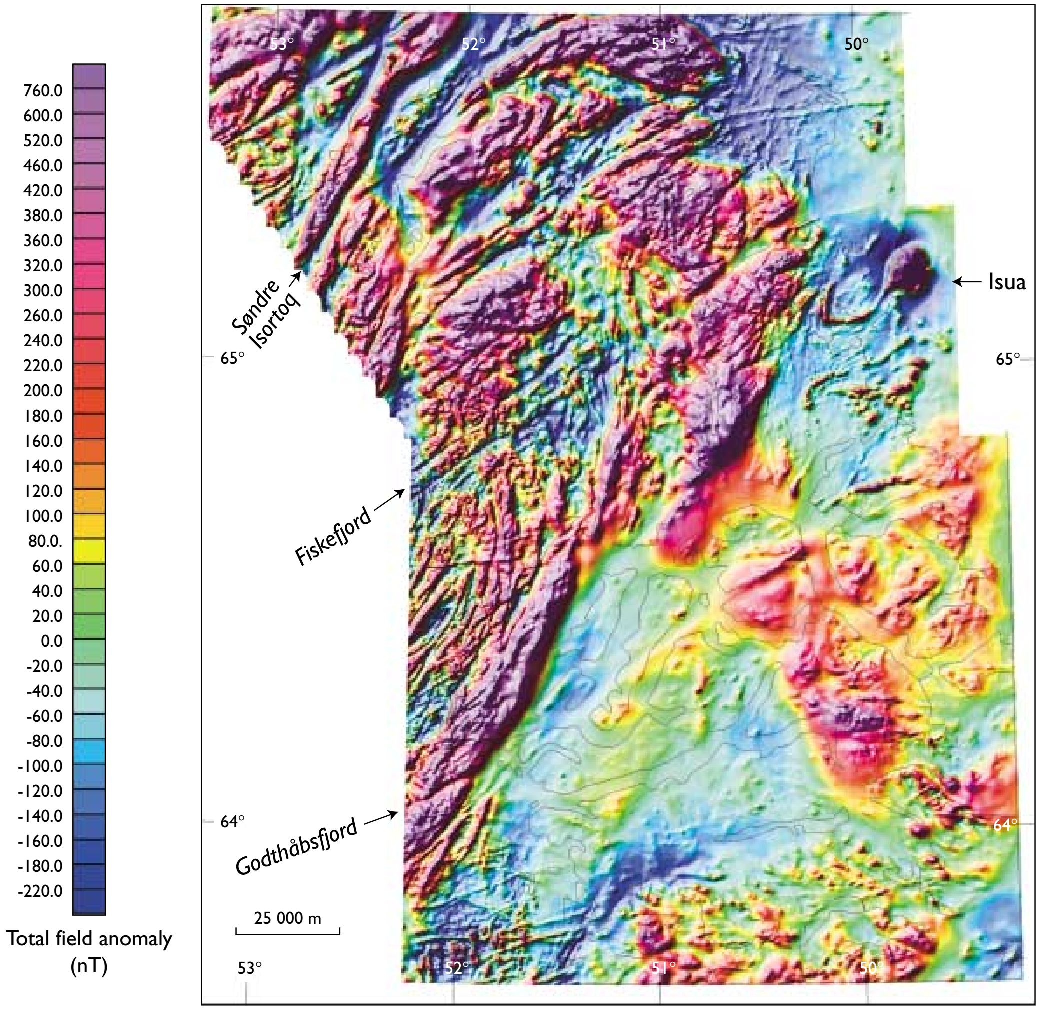

Fig. 2. Magnetic total field intensity with shadow for the area in southern West Greenland covered by project Aeromag 1998. For location see Fig. 1.

an irregular shaped area between 51°W and 52°W was excluded because of coverage by an existing data set obtained in 1995 by project AEM Greenland 1995 (Stemp 1996). In Fig. 2 the two surveys are merged to give a homogeneous data set for the entire region. The measurements were carried out by a fixed-wing aircraft following a gentle drape surface 300 m above the ground. The survey lines with a separation of 500 m were aligned in a N–S direction. Orthogonal tie-lines were flown with a separation of 5000 m.

Sander Geophysics Ltd., Canada flew the survey between 31 March and 13 July, 1998, using two geophysically equipped Cessna Grand Caravan aircraft operating out of the airport in Nuuk. The magnetic base station utilised for correction of magnetic diurnal variations was placed adjacent to the runway. Diurnals were quite active throughout the entire period of the survey. Further details of the survey operation and equipment can be found in a report by Sander Geophysics Ltd. (1998), which is supplied with a digital data package that can be purchased from GEUS

Maps at scales of 1:250 000 and 1:50 000 have been produced from the data. The total magnetic field anomaly data provide a wealth of structural information, as can be seen in Fig. 2. Among the most spectacular anomalies in the area is the 20 000 nT anomaly in the Isua area. Differences in magnetic properties of those parts of the crust dominated by granulite facies rocks

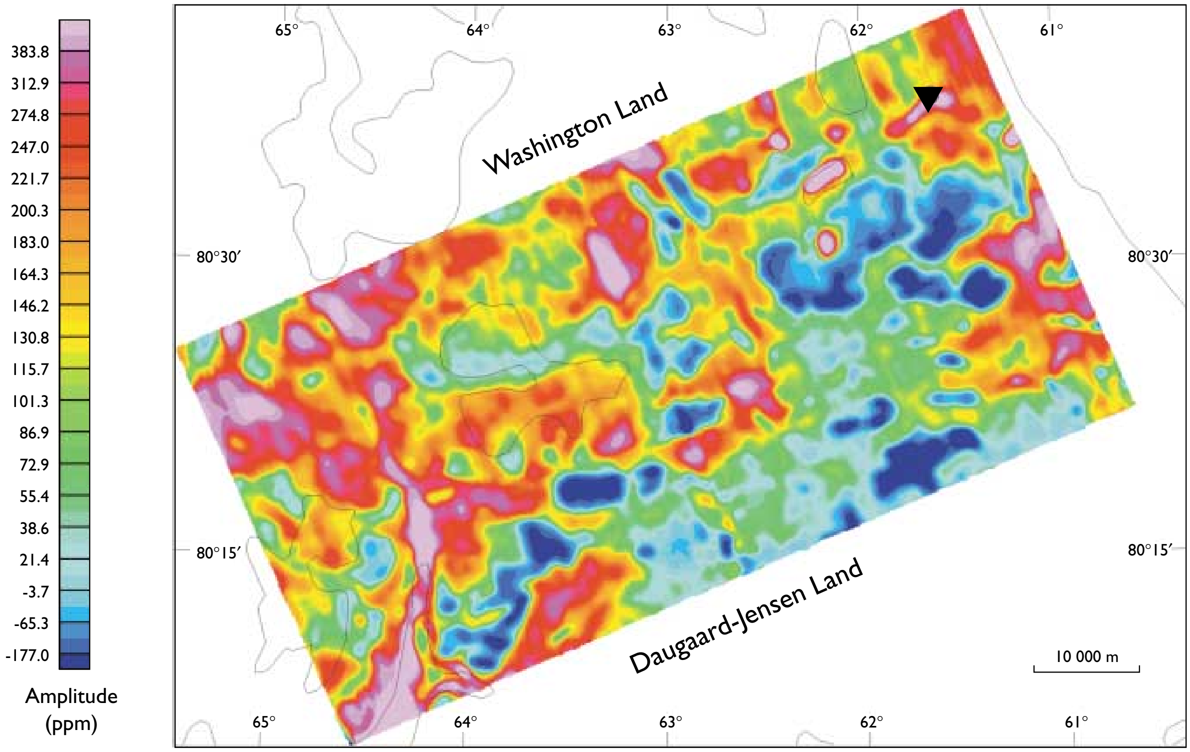

Fig. 3. Amplitude in ppm with respect to max. signal strength of the vertical component for the GEOTEM system channel 10 in Washington Land and Daugaard-Jensen Land, western North Greenland. The location of the Zn-Pb-Ag mineralisation is indicated by a black, inverted triangle. For location see Fig. 1.

and those parts dominated by amphibolite facies rocks are reflected clearly in the wavelength of the anomalies. The rocks in granulite facies are characterised by anomalies of short wavelength with high amplitudes whereas the amphibolite facies rocks cause more gentle variations of the magnetic field.

As part of project Aeromag 1998, a detailed survey was flown in the Disko Bugt area covering an arc-shaped magnetic feature with a radius of about 10 km. This had been revealed from the Aeromag 1997 data. The greater part of the survey area was over water of Disko Bugt and only the south-west portion was over the island of Disko which rises to more than 800 m above sea level. Line spacing for this survey was 250 m with a total of 1755 line km flown. The survey altitude was 120 m above ground or sea level.

AEM Greenland 1998

Project AEM Greenland 1998 included surveys of an area of 3200 km^2 in Washington Land and Daugaard-Jensen Land, western North Greenland, 1650 km^2 in J.C. Christensen Land, eastern North Greenland and 485 kilometres of reconnaissance lines in eastern Peary Land, central North Greenland (Fig. 1). The project was carried out as a combined transient electromagnetic (GEOTEM) and magnetic survey, and was flown by Geoterrex-Dighem Ltd., Canada. Nominal flight height was 120 m over the terrain with total field magnetic sensor and electromagnetic sensor at heights above ground of 75 m and 70 m, respectively. The base frequency for the GEOTEM system was 90 Hz. The survey was flown using two geophysically equipped Casa aircraft during the period from 29 May to 24 June, 1998.

A Zn-Pb-Ag mineral occurrence discovered in 1997 (Jensen & Schønwandt 1998) led to the selection of Washington Land and Daugaard-Jensen Land in western North Greenland as one of the target areas for the AEM Greenland 1998 project (Fig. 1). The mineralisation is within exposed Lower Palaeozoic carbonate deposits. The surveyed area is indicated in Fig. 1 as AEM Greenland 1998(1). The survey was flown out of Alert in Canada using a line separation of 400 m. A smaller area cover-

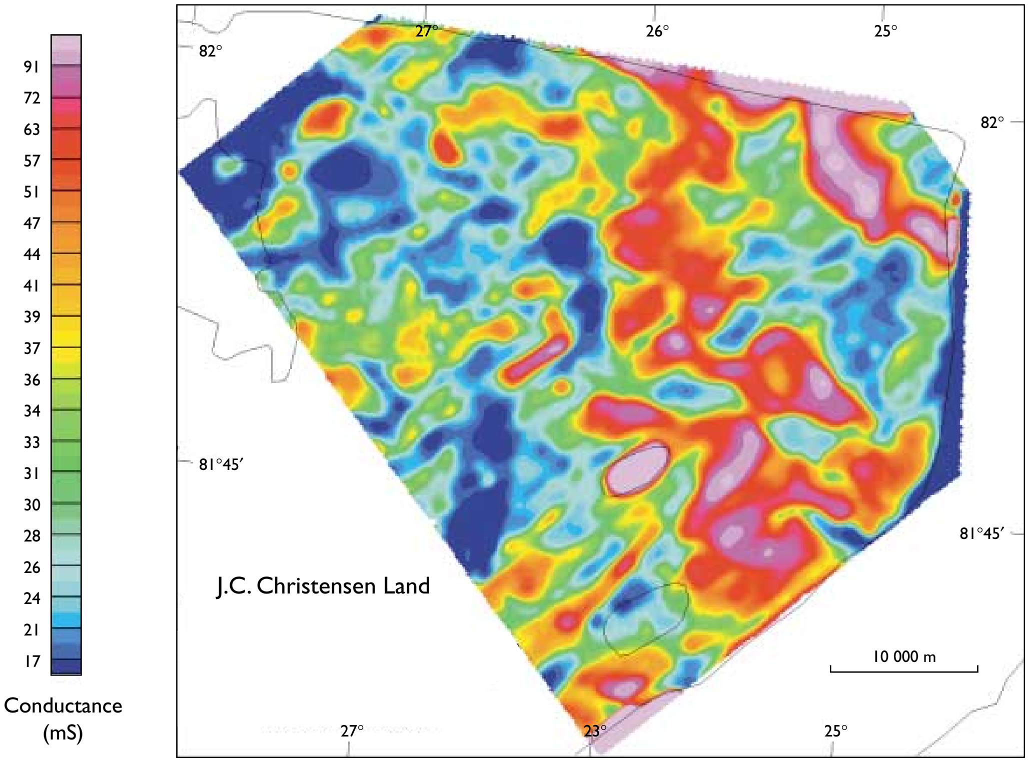

Fig. 4. Estimated apparent conductance from the survey in J.C. Christensen Land, eastern North Greenland. For location see Fig. 1.

ing the mineral occurrence was flown with lines at a different orientation separated by 200 m and at lower altitude. Tie-lines with a separation of 4000 m were flown in the direction orthogonal to the ordinary survey lines. A total of 9321 line km were flown. The base station used for correction of magnetic diurnal variations was placed in Alert, Ellesmere Island, Canada (Fig. 1). Further details of the survey operation and equipment can be found in a report by Geoterrex-Dighem Ltd. (1998a), which is supplied with purchase of the digital data package. The maps produced from the survey are of six types: total magnetic field and associated vertical derivative, amplitudes of the vertical component for GEOTEM channel 10, apparent conductance, GEOTEM anomalies with flight lines and a separate topographic sheet. The maps are available at scales 1:250 000 and 1:50 000 for the entire survey area, and at scale 1:20 000 from the detailed survey covering the mineral occurrence. An example of the data shows the amplitude of the vertical components for off-time channel 10 of the GEOTEM system (Fig. 3) for the entire survey area and the position of the mineral occurrence. A detailed description of the measured data can be found in Rasmussen (1999a). Several targets for a follow-up search for mineralisation showings can be identified from the new data.

The survey in J.C. Christensen Land, eastern North Greenland, was flown out of Station Nord (Fig. 1), and comprises 4492 line km of data. The surveyed area is indicated in Fig. 1 as AEM Greenland 1998(2). Survey parameters and map products are similar to those of the survey in Washington Land and Daugaard-Jensen Land. A comprehensive summary is found in the processing report by Geoterrex-Dighem Ltd. (1998b). A description of the data and discussion of the results can be found in Rasmussen (1999b). Copper-sulphide mineralisations constitute the main target for this survey. The geology of J.C. Christensen Land is dominated by undeformed Mesoproterozoic sandstones and mafic volcanic rocks, overlain to the north-east by Neoproterozoic and Lower Palaeozoic sedimentary successions. An example of the acquired data (Fig. 4) shows the calculated apparent conductance.

A large number of conductivity anomalies were revealed by a reconnaissance flight in eastern Peary

Land, central North Greenland indicated in Fig. 1 as AEM Greenland 1998(3). This part of the survey was flown with a nominal height of 120 m, but the severe topography caused some problems flying at a low altitude. The magnetic data indicate the presence of an igneous structure not previously recognised. The data from the reconnaissance flight are presented in the reports covering the survey in J.C. Christensen Land (Geoterrex-Dighem Ltd. 1998b; Rasmussen 1999b).

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Upernavik 98: reconnaissance mineral exploration in North-West Greenland

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The Upernavik 98 project is a one-year project aimed at the acquisition of information on mineral occurrences and potential in North-West Greenland between Upernavik and Kap Seddon, i.e. from 72°30′ to 75°30′N (Fig. 1A). A similar project, Karrat 97, was carried out in 1997 in the Uummannaq region 70°30′–72°30′N (Steenfelt *et al.* 1998a). Both are joint projects between the Geological Survey of Denmark and Greenland (GEUS) and the Bureau of Minerals and Petroleum (BMP), Government of Greenland, and wholly funded by the latter. The main purpose of the projects is to attract the interest of the mining industry. The field work comprised systematic drainage sampling, reconnaissance mineral exploration and spectroradiometric measurements of rock surfaces.

The region of the 4500 km^2 project, which covers most of Upernavik kommune and the southernmost part of Qaanaap (Thule) kommune, consists of islands, peninsulas and nunataks with relatively gentle topographic relief. Operating in the region by boat is not without problems. The main obstacle is the sea ice, especially calf ice in the so-called 'isfjorde' which drain directly from the Inland Ice. Starting the work in the southern part of the region and progressing towards the north for 330 km to reach Kap Seddon in mid-August, ensured that reasonable ice conditions were encountered in all areas.

The field work was carried out by a team of three geologists (B.T., J.K., T.T.) and two local assistants during eight weeks in July–August 1998. A chartered 36 foot vessel served as a mobile base working from 18 anchorages – M/S *Sila* (see Frontispiece of this volume, p. 3). Two rubber dinghies were used for local transport to all coastal localities while an AS 350 helicopter was chartered for six days to cover inland areas. The weather was relatively stable with only five days lost due to bad weather.

Geological outline

The project region is underlain by the Precambrian shield capped by Tertiary sediments and flood basalts in the southernmost part (Fig. 1A). The shield is composed of an Archaean gneissic basement with a cover of Palaeoproterozoic sediments (Fig. 2). These were folded and metamorphosed at granulite facies, and north of 73°15′N at amphibolite facies, during the Rinkian (Hudsonian) orogenesis around 1.85 Ga. Fold styles are dominantly overturned to nearly recumbent sheath folds involving both gneiss and metasediments (Grocott & Pulvertaft 1990). In the south a major syn-tectonic granitic complex exists, and the whole area is transected by a swarm of 1.65 Ga, NNW–SSE striking dolerite dykes (Nielsen 1990). The main part of the region was mapped in the period 1977–79 by the Geological Survey of Greenland at a scale of 1:100 000 (Escher & Stecher 1978, 1980); the northernmost part was mapped at 1:200 000 in 1980 (Dawes 1991).

The Archaean basement consists of intensely folded tonalitic to granodioritic gneisses with lenses and layers of metasediments, and mafic to ultramafic rocks. To the north, in the Kap Seddon area, the basement also contains thin horizons of banded iron formation (Dawes & Frisch 1981).

The Palaeoproterozoic metasediments belong to the Karrat Group (Henderson & Pulvertaft 1967, 1987), which continues southwards to *c.* 70°N where it hosts the abandoned 'Black Angel' lead-zinc mine (Pedersen 1980, 1981; Thomassen 1991). The Karrat Group has been correlated with coeval sediments of the Foxe Fold Belt in Canada (Grocott & Pulvertaft 1990). Based on U–Pb isotope data on detrital zircons from the Uummannaq region, it is estimated that deposition took place about 2 Ga ago (Kalsbeek *et al.* 1998). In the project region the Karrat Group comprises two formations. The lower, Qeqertarssuaq Formation, is developed as an intensely sheared unit, less than 50 m thick, of vari-

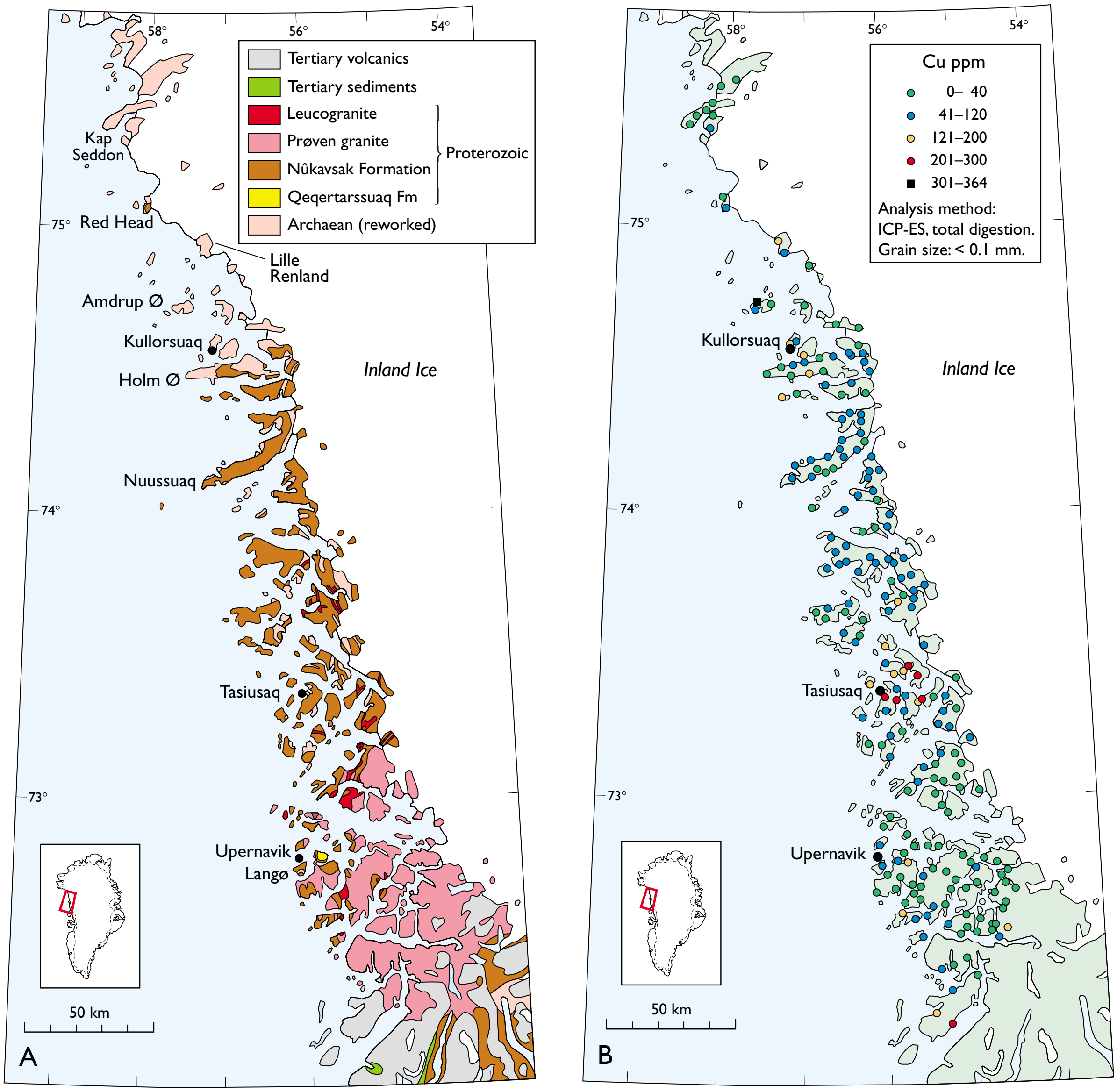

Fig. 1. Maps of the project region. **A**: Geological map based on Grocott & Pulvertaft (1990) and Dawes (1991). **B**: Geochemical map of Cu concentrations in the < 0.1 mm fraction of stream sediment samples.

able proportions of pelitic and graphitic schists, marble, skarns and quartzite of marine to open shelf origin. Minor layers of amphibolite are believed to represent metavolcanic rocks. The upper Nûkavsak Formation is a 1.5 km or more thick succession of monotonous, often rusty-weathering metagreywackes interpreted as flysch sediments deposited during a later transgression (Escher & Stecher 1980). The metagreywackes of the Upernavik – Kap Seddon region (Fig. 1A) are commonly migmatised with a gneissic character, unlike their less metamorphosed counterparts in the Uummannaq region to the south (70°30′–72°30′N).

The Prøven granite is a hypersthene-bearing igneous complex of various granitic units with an age of *c.*1.86 Ga (Kalsbeek 1981). The two main types are coarse-grained granites commonly with porphyritic feldspar forming massive sheets, and more fine-grained leucogranites occurring as irregular sheets and veins.

During the field work it was noticed that erratic boulders of undeformed, reddish brown sandstone and mud-

Fig. 2. Typical basement–cover section in an 800 m high, south-west-facing cliff east of Holm Ø. Rusty Karrat Group metasediments rest on grey Archaean gneiss.

stone with cross-bedding and mud cracks are widespread in the Tasiusaq area, indicating the existence of such post-orogenic sediments towards the east beneath the Inland Ice. These rocks form a redbed assemblage not unlike some lithologies of the Proterozoic Thule Supergroup (Dawes 1997).

The Tertiary rocks present in the southernmost part of the region were not studied during the 1998 field work.

Geochemical survey

The geochemical survey was a northerly continuation of the 1997 geochemical mapping of the Uummannaq region (Steenfelt *et al.* 1998a, b) and comprised collection of stream sediment and water samples at a nominal density of one sample per 15 to 20 km^2 of the land surface. Prior to the field work preferred sample sites were selected and marked on aerial photographs. An attempt was made to obtain an even distribution of sample localities in first or second order streams with drainage basins not larger than 10 km^2. In total, 238 sites were sampled. The fine fractions (< 0.1 mm) of the stream-sediment samples were used for analyses. Major elements were determined at the Survey by X-ray fluorescence spectrometry using fused samples, while trace elements were determined at Activation Laboratories Ltd., Canada by a combination of instrumental neutron activation analysis and inductively coupled plasma emission spectrometry. The analytical results are summarised in Table 1.

Many element distributions show geochemical patterns related to lithology. Thus the area south of 73°N, dominated by the Prøven granite, is characterised by elevated Ba, Sr, Ti, V and Y, while the area north of Holm Ø, dominated by basement gneisses, has elevated Sr and Ti and low levels of U, Th, K and Pb. The Karrat Group rocks, in the central area, have higher As, U, Th, Cu and Zn than the basement to the north. The most interesting geochemical feature, interpreted to indicate mineralisation, is a cluster of samples at Tasiusaq with high values of Cu (Fig. 1B). In the same area there are also anomalies of Au, Co, Cr, La, Mo, Ni, Th, U, V and Zn. In the vicinity of Kullorsuaq there are some high zinc and copper values and one gold anomaly.

Mineral exploration

From a mineral exploration point of view, the Upernavik – Kap Seddon region is one of the least explored parts of Greenland. Minor amounts of graphite were quarried on Langø near Upernavik in 1845 (Ball 1923) and samples of sphalerite were collected on Red Head at the beginning of the century (Bøggild 1953). Four short reconnaissance visits have been carried out by mining companies in the period 1969–81 (viz. Stuart Smith & Campbell 1971; Neale & Stuart Smith 1973; Brunet 1980; King 1981). During mapping by the former Geological Survey of Greenland some malachite staining and iron sulphides were reported from the basal part of the Karrat Group (Escher & Stecher 1980), while the scattered

Table 1. Statistical parameters for major and trace elements of stream sediment samples between Upernavik and Kap Seddon, North-West Greenland

	Min.	Max.	Med.	98 pc.	An. meth.
SiO_2	30.35	73.59	64.67		XRF
TiO_2	0.29	5.21	0.78		XRF
Al_2O_3	7.0	25.13	15.37		XRF
Fe_2O_3	2.26	28.83	7.07		XRF
MnO	0.03	0.29	0.08		XRF
MgO	0.67	18.65	1.93		XRF
CaO	0.86	15.57	2.18		XRF
Na_2O	0.37	4.54	2.63		AAS
K_2O	0.25	4.98	3.27		XRF
P_2O_5	0.11	3.47	0.27		XRF
As	<0.5	110	2.7	20	INAA
Au (ppb)	<2	32	<2	12	INAA
Ba	<100	2000	650	1478	INAA
Co	3	150	14	48	INAA
Cr	14	3000	73	203	INAA
Cu	6	364	41	219	ICP-ES
Hf	1	140	15	50	INAA
Mo	<2	87	<2	30	ICP-ES
Ni	7	1193	31	100	ICP-ES
Pb	<5	81	32	50	ICP-ES
Rb	<5	200	110	180	INAA
Sb	<0.1	0.6	<0.1	0.4	INAA
Sc	4.7	45	15	29	INAA
Sr	49	1022	175	392	ICP-ES
Th	0.9	170	33	98	INAA
U	<0.5	31	5.4	21	INAA
V	22	549	86	280	ICP-ES
Y	14	80	36	72	ICP-ES
Zn	24	223	83	182	ICP-ES
La	7.9	489	100	268	INAA
Ce	19	600	193	520	NAA
Nd	10	270	74	195	INAA
Sm	1.5	40	13	32	INAA
Eu	<0.2	7.2	1.4	4.1	INAA
Yb	<0.2	7	2.7	5.9	INAA
Lu	<0.05	1.2	0.5	1.0	INAA

Analytical methods (An. meth.) for the < 0.1 mm grain size fraction of 240 stream sediment samples.
XRF: x-ray fluorescence spectrometry by the Survey, Copenhagen.
INAA: instrumental neutron activation analysis by Activation Laboratories Ltd., Canada.
ICP-ES: inductively coupled plasma emission spectrometry by Activation Laboratories Ltd., Canada.
AAS: atomic absorption spectrometry by the Survey, Copenhagen.
Statistical parameters: minimum (Min.), maximum (Max.), median (Med.) and the 98th percentile (98 pc.).
Major elements in percent, trace elements in ppm, except Au, ppb.

occurrences of banded iron formation mapped at Kap Seddon represent the southern exposures of the regional magnetite province that stretches north-westwards for 350 km along the Lauge Koch Kyst of Melville Bugt as far north as 76°30′N (Dawes & Frisch 1981).

The 1998 exploration work was mainly carried out as shoreline exploration, i.e. visual inspection of the coastal exposures for signs of mineralisation while passing slowly in a rubber dinghy. Prospective localities were investigated by sampling of mineralised boulders, scree, and *in situ* rock, and by the panning of stream sediments. A few localities were visited on helicopter stops. Before the field season, a remote sensing study of rust zones based on Landsat TM imagery was carried out and maps showing the zones of more intense ferric iron staining were produced for use in the planning of field visits. The samples have been analysed at Activation Laboratories Ltd., Canada for a suite of elements including precious and base metals. The main results are summarised below.

Archaean basement

Malachite staining caused by weathering of disseminated chalcopyrite was observed in some of the mafic–ultramafic lenses and layers in the basement gneisses north of Kullorsuaq (Fig. 1A). The most extensive mineralisation was found on Amdrup Ø where malachite patches are scattered over a 50–100 m high cliff of mafic gneisses. Sulphide-bearing grab samples from this locality contain up to 0.59% Cu and 57 ppb Au. On Lille Renland 25 km further north, a grab sample from a *c.* 5 m thick lens of hornblendite of magmatic origin shows surprisingly high precious-metal values: 0.25% Cu, 554 ppb Au, 477 ppb Pt and 1073 ppb Pd.

Scattered malachite staining was also observed over a more than one kilometre strike length in leucogneiss not far below the base of the Karrat Group on north-eastern Nuussuaq. A grab sample of biotite-rich gneiss from this locality with traces of chalcopyrite returned 0.06% Cu, 145 ppb Au and 79 ppm Bi. Local blocks of reddish, brecciated granite with pyrite and fluorite were sampled on Amdrup Ø and Holm Ø, but analyses show nothing noteworthy in these rocks.

The banded iron formation at Kap Seddon was sampled at two localities 9 km apart that probably represent the same 0.5–1.0 m thick horizon. In addition to magnetite and iron silicates, minor disseminated pyrrhotite and chalcopyrite were observed. Samples returned up to 32% Fe, 0.24% Mn, 0.1% Cu and 5 ppb Au. Banded iron formation was not encountered south of this area, but it was noted that the gneisses of the Kullorsuaq area are rich in disseminated magnetite.

Karrat Group

The basal, thin unit of the Karrat Group (Qeqertarssuaq Formation) was regarded as a prime exploration target because of its diversified lithologies. Strongly deformed layers and lenses of graphite schist with variable iron sulphide content were mainly encountered north of Tasiusaq. The graphite grades were not inspected more closely but it was noted that the old pits on Langø (mentioned above, see Fig. 1A) are only a few metres in each dimension corresponding to the size of the graphite lenses mined. Semi-massive pyrrhotite-pyrite lenses sampled in the Nuussuaq – Holm Ø area show similarities with the iron sulphide horizons in the Nûkavsak Formation in the Uummannaq region to the south (Thomassen 1992; Thomassen & Lind 1998). The sulphide-rich graphite schist is especially conspicuous on the south coast of Holm Ø, where it forms a spectacular folded 5–10 m thick horizon. The highest base-metal values were encountered on north-eastern Nuussuaq, where the 5 m thick horizon crops out *c.* 20 m above the contact with the basement gneiss. Grab samples of semi-massive pyrrhotite-pyrite with sphalerite and chalcopyrite contain up to 2.43% Zn, 0.21% Cu, 21 ppb Au, 96 ppb Pt and 100 ppb Pd.

Carbonate rocks range from pure, white calcite marble to green diopside marble, grey scapolite marble and other rocks rich in calc-silicate minerals. They may contain sporadic disseminated sulphides. The highest

Fig. 3. Typical, *c.* 1 km wide rust zone in Karrat Group metasediments on Red Head. View towards the north.

base-metal values (0.57% Zn and 0.03% Pb) stem from a grab sample of diopside marble with minor sphalerite, pyrrhotite and graphite from eastern Holm Ø. A scheelite-bearing block of calc-silicate rock from southern Holm Ø returned 744 ppm W.

The upper, thick unit of the Karrat Group (Nûkavsak Formation) hosts conspicuous red and yellow rust zones of regional extent which are especially well developed in the Tasiusaq region and on Red Head (Fig. 3). The extent of these zones is well displayed on Landsat rust anomaly maps which show that they are almost exclusively confined to the western parts of the area. The absence of rust zones or rust-stained rocks close to the ice margin is probably due to recent glacial erosion. In the field it was observed that the rust zones consist of conformable, tens of metres thick units, which only differ from the neighbouring grey metagreywackes by a somewhat higher content of biotite, graphite and minor pyrrhotite and magnetite. No signs of semi-massive sulphide concentrations were observed, but the stream sediment anomalies suggest that mineralisation has occurred. The analysed rock samples show no significant metal concentrations apart from 125 ppb Au in a chip sample of a 10 cm thick pyrite-bearing chert from Red Head.

Malachite staining was observed in metasediments near the contact to the Prøven granite 30 km east of Upernavik, where minor blebs of chalcopyrite (up to 0.18% Cu) occur in pelite intruded by granitic veins. In the same area, a number of arsenopyrite-bearing, quartzitic boulders returned up to 0.34% As and 111 ppb Au.

Spectroradiometric measurements

A programme of spectroradiometric measurements was carried out during August by using a GER Mark V Infrared Intelligent Spectroradiometer, which provides accurate spectral measurements from 350 to 2500 nm in 704 channels. The objective was to determine spectral characteristics of representative lithologies and various types of hydrothermal alteration. The effect of partial lichen cover on the spectral characteristics of rocks was measured in selected localities. The measurement programme was combined with collection of representative rock samples from each investigated locality. The results of the spectroradiometric survey will provide an accurate reference data set for a more sophisticated processing and interpretation of available multispectral satellite data and future hyperspectral data sets from air- and satellite-borne sensors.

Concluding comments

Archaean basement

The copper mineralisation associated with mafic and ultramafic rocks in the northern part of the region holds a potential for magmatic gold and platinum group elements. However, further investigations are required to clarify the extent, characteristics and economic significance of this mineralisation.

Although no economic metal values were detected in the banded iron formation in the northernmost part of the project region, its regional extent northwards for 350 km into Qaanaap kommune invites further exploration (Dawes & Frisch 1981).

Karrat Group

The rust zones of the Upernavik – Kap Seddon region apparently do not host semi-massive sulphide concentrations, as found in the Uummannaq region, and the coloration seems merely to stem from breakdown of biotite and oxidation of minor sulphides in the metasediments. However, the one horizon in the Upernavik – Kap Seddon region with semi-massive sulphides, in the Qeqertarssuaq Formation at the very base of the Karrat Group, has yielded a promisingly high zinc value of 2.4%. This target certainly deserves follow-up investigations for shale-hosted base metal deposits. Furthermore, the source of the multi-element stream-sediment anomalies in the Karrat Group metasediments should be determined.

The marbles in the Upernavik – Kap Seddon region are normally only a few metres thick (max. 30 m according to Escher & Stecher 1980) in contrast to those of the Uummannaq region, where they may be several hundreds of metres thick and host Pb-Zn ores of the Black Angel type (Pedersen 1980, 1981; Thomassen 1991). Lead-zinc mineralisation in interfingering thin marbles and pelites is, however, also known from the Uummannaq region (Thomassen & Lind 1998), and this lithology is widespread in the Qeqertarssuaq Formation of the Upernavik – Kap Seddon region. It is therefore believed that the carbonate components of the Qeqertarssuaq Formation add to the prospectivity of this unit.

Arsenopyrite mineralisation with enhanced gold, common in the northern part of the Uummannaq region (Thomassen 1992; Thomassen & Lind 1998), has only been recognised in the southernmost part of the Upernavik – Kap Seddon region, corresponding to relatively low arsenic concentrations in the stream sediment samples from this region (Table 1).

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Petroleum geological activities in West Greenland in 1998

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In the last few years there has been renewed interest for petroleum exploration in West Greenland and licences have been granted to two groups of companies: the Fylla licence operated by Statoil was awarded late in 1996; the Sisimiut-West licence operated by Phillips Petroleum was awarded in the summer of 1998 (Fig. 1). The first offshore well for more than 20 years will be drilled in the year 2000 on one of the very spectacular structures within the Fylla area.

To stimulate further petroleum exploration around Greenland – and in particular in West Greenland – a new licensing policy has been adopted. In July 1998, the administration of mineral and petroleum resources was transferred from the Danish Ministry of Environment and Energy to the Bureau of Minerals and Petroleum under the Government of Greenland in Nuuk. Shortly after this, the Greenlandic and Danish governments decided to develop a new exploration strategy. A working group consisting of members from the authorities (including the Geological Survey of Denmark and Greenland – GEUS) made recommendations on the best ways to stimulate exploration in the various regions on- and offshore Greenland. The strategy work included discussions with seismic companies because it was considered important that industry acquires additional seismic data in the seasons 1999 and 2000.

The new strategy was presented in April 1999 (see the Survey's *Ghexis Newsletter* 15 for details, or the Bureau of Minerals and Petroleum's homepage: www.bmp.gl). A licensing round will be held in the year 2001 for areas offshore West Greenland between 63° and 68°N, and an open door policy will be re-established for areas from 60° to 63°N and from 68° to 71°N offshore West Greenland from October 1999 (Fig. 1).

On Nuussuaq grønArctic Energy Inc., a small Canadian company, had to relinquish their licence early in 1998 due to problems in raising finance for the next part of their exploration commitments. To ensure that other interested companies have sufficient time to evaluate the exploration potential of the Disko–Nuussuaq region, the authorities decided in the summer of 1998 that all applications received before 1 October, 1999 will be handled in one process. If no applications are received before this closing date, the area will be covered by the same open door policy as operates in the neighbouring offshore areas.

Recent developments, with new exploration both on- and offshore West Greenland in the 1990s, have been strongly driven by encouraging research results. Some of the most important break-throughs were made in the offshore area where new seismic data revealed large structures, either tilted fault blocks or compressional features, on seismic lines and direct hydrocarbon indicators in the form of flat spots (Bate *et al.* 1994; Chalmers *et al.* 1995). The discovery of extensive seepage of different oil types in the Disko – Nuussuaq – Svartenhuk Halvø area, providing evidence of multiple oil-prone source rocks in this area has also been very important in attracting industry to the region (Christiansen *et al.* 1996; Bojesen-Koefoed *et al.* 1999).

Based on previous successes several new research projects were initiated in 1998, and more will follow in 1999 and the years to come. The projects cover most aspects of petroleum geology and geophysics both on- and offshore West Greenland. Some of these are highlighted at the end of the present article, which also provides a brief account of the field work carried out in 1998; reviews of recent summaries of results from grønArctic's GRO#3 well from which data have been released, and of recent GEUS and industry activities offshore, are also given.

Field work in the Disko–Nuussuaq region

The aim of the field work in 1998 was mainly to complete previous sedimentological and structural studies

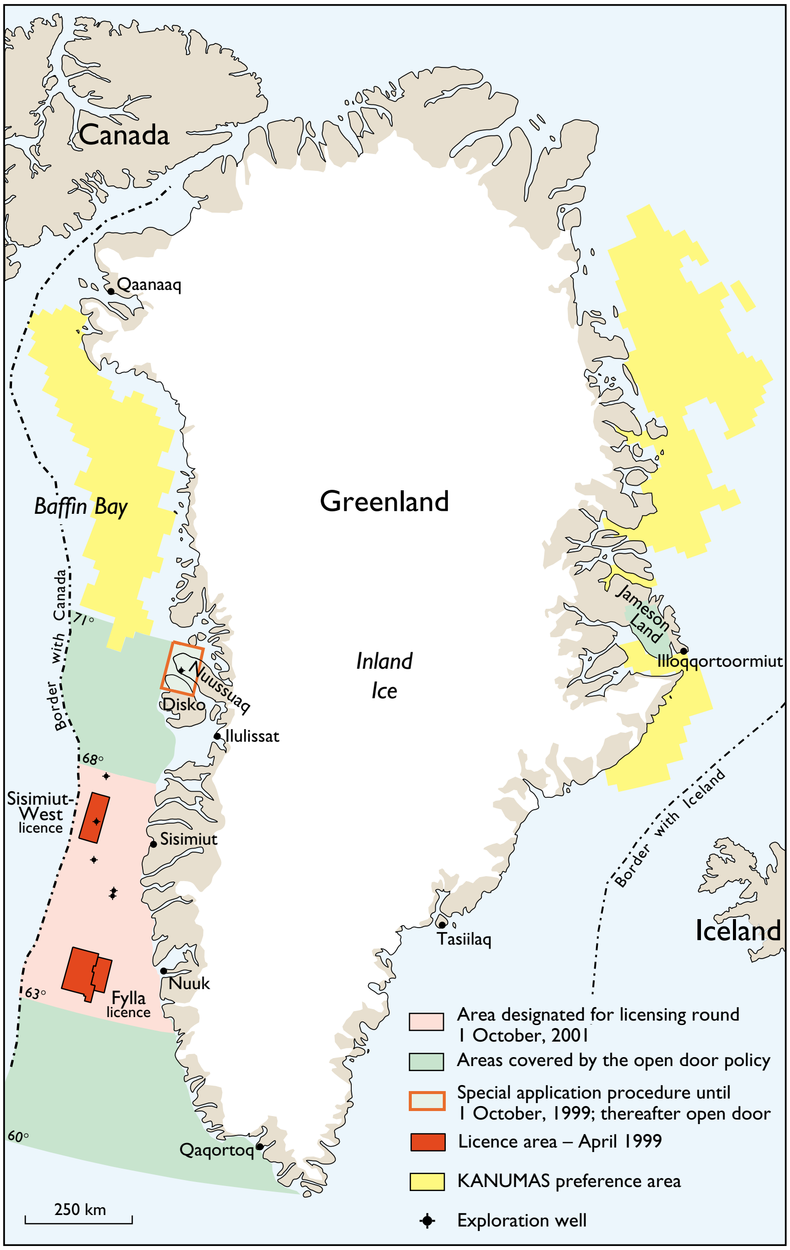


Fig. 1. Map showing areas offshore Greenland to be opened in a new licensing round, areas covered by an open door policy, KANUMAS preference areas, and licence areas. Modified from the Survey's *Ghexis Newsletter* 15, (April 1999).

on Nuussuaq and Hareøen (Fig. 2). Some additional sampling of oil seeps was also carried out and guidance was provided for a field party from the Atlantic Margin Group (Statoil, Mobil and Enterprise Oil) that studied the volcanic rocks in the area (Ellis & Bell 1999).

The sedimentological field work was concentrated on four main tasks: (1) correlation of sections through the Atane Formation, (2) sampling of the Paleocene Naujât Member, (3) measuring and sampling a Neogene–Quaternary section on Hareøen, and (4) a detailed study of tectonically controlled unconformities of early Campanian and early Paleocene age.

Atane Formation

The Atane Formation is well exposed at Kingittoq in south-eastern Nuussuaq (Fig. 2), where a sedimentary section was measured and the basal part of the lacus-

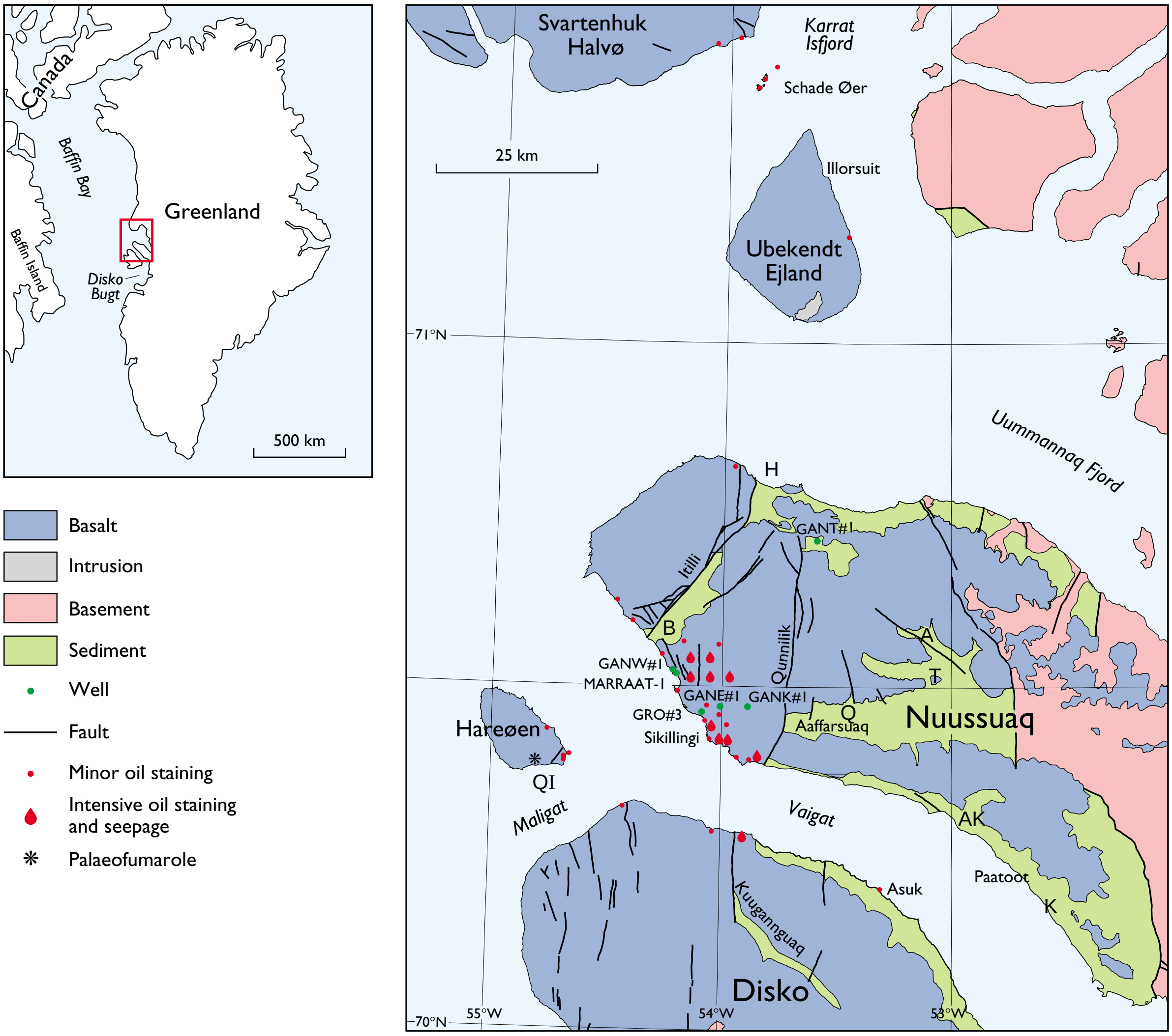


Fig. 2. Simplified geological map of the Disko – Nuussuaq – Svartenhuk Halvø area showing the position of wells and boreholes, and distribution of localities with seepage and staining of oil found in the period 1992–98. **A**: Agatdalen (with Baculiteskløft and Scaphitesnæsen). **AK**: Atlaata Kuua. **B**: Bartschiakløft. **H**: Hollænderbugt. **K**: Kingittoq. **Q**: Qilakitsoq. **QI**: Qaassuup Illui. **T**: Tunoqqu. Based on published Survey maps.

trine Naujât Member (Paleocene) was sampled. Previous samples from this part of the Naujât Member have yielded only badly preserved palynomorphs, and in order to test a depositional model additional material was collected with a view to establishing the proportion of reworked palynomorphs from older stratigraphic levels.

Neogene–Quaternary section on Hareøen

Throughout most of the Nuussuaq Basin the Paleocene sediments are overlain by volcanic rocks succeeded by Quaternary deposits. On Hareøen, however, a succession of Neogene sediments overlies lava flows of the Talerua Member. These sediments were studied and sampled. Palynological data from these sediments are expected to provide information on biostratigraphy and palaeoclimate during the post-volcanic period in the Nuussuaq region. The oldest post-volcanic sediments are interpreted as having been deposited after fumarolic activity (Fig. 3) and may thus provide biostratigraphic constraints on the age of the Talerua Member. The fumarolic activity was followed by deposition of a thin coal bed with abundant resinite (Fig. 4). The coal is overlain by a thick succession of clastic sediments which have been closely sam-

Fig. 3. The palaeofumarole at Qaassuup Illui, southern part of Hareøen. The white rocks are strongly altered lavas of the Talerua Member, and the palaeofumarole is outlined by a thin coal layer (Fig. 4). The overlying clastic sediments are Neogene in age. Height of cliff face *c.* 50 m.

Fig. 4. Coal with abundant resinite, Qaassuup Illui, Hareøen. Largest piece of resinite is *c.* 1 cm.

pled to obtain material for dating and identification of the start of glacial influence in West Greenland.

Evidence for an early Campanian tectonic unconformity

From work in Disko Bugt in the early 1990s it became apparent that an unconformity is present in central Nuussuaq separating the deltaic deposits of the Atane Formation below from the overlying gravity flow deposits distinguished as a new member (Aaffarsuaq Member; Dam *et al.* in press). This unconformity is especially well exposed along the northern slopes of the Aaffarsuaq valley between Qilakitsoq and Tunoqqu (Fig. 2). However, the age of the unconformity was very uncertain, mainly because the biostratigraphic work on ammonites by Birkelund (1965) was never followed up by the establishment of a formal lithostratigraphic framework for all the marine Cretaceous strata. Moreover, the sample localities in the Aaffarsuaq valley were very poorly defined and the marine palynoflora in this part of the basin is very poor. In the Agatdalen area Birkelund's sampling localities are much better known, and on the basis of detailed mapping in 1998 in this area, it is now possible to place Birkelund's (1965) localities and the shallow wells drilled in 1992 in Agatdalen (cf. Christiansen *et al.* 1994) in a lithostratigraphic framework (G. Dam *et al.,* unpublished data). The marine palynoflora in Agatdalen is rich and on the basis of a combination of the new lithostratigraphic and biostratigraphic data combined with Birkelund's ammonite study it has been possible to date the unconformity more precisely (G. Dam *et al.*, unpublished data). The palynoflora and the ammonites from the uppermost part of the Atane Formation in Baculiteskløft have a late Santonian age, whereas the ammonites in the Aaffarsuaq Member at Scaphitesnæsen indicate a latest early Campanian age (cf. Birkelund 1965). The marine palynoflora from this member indicates an early to mid-Campanian age. From these ages it can be concluded that the unconformity has an early Campanian age (G. Dam *et al.*, unpublished data).

Structural studies on Nuussuaq

Structural field studies for an ongoing Ph.D. project by Anders Boesen were completed during the 1998 season. An area west of Hollænderbugt on the north coast of Nuussuaq was visited with special emphasis on the fracture zone related to the Itilli fault. The area is poorly exposed but it has been possible to correlate some of the onshore structures to the offshore seismic lines north of Nuussuaq. On the offshore seismic line south of Nuussuaq it is also possible to extrapolate the Itilli fault whereas the very complex fault system seen at Bartschiakløft west of the Itilli fault is unrecognisable in the seismic data.

Oblique colour stereophotography was carried out from a helicopter in the area around Bartschiakløft to gain a better understanding of the relationships between faults and dykes. Additional sampling of dykes in the Bartschiakløft area was carried out to improve the geochemical correlation between dykes and the known lava succession. Preliminary results suggest that there are three distinct groups of dykes which can be related to the structural history.

Palaeogene volcanic rocks

During 1998 volcanic rocks were sampled from the faulted and poorly exposed areas with oil-impregnated rocks on the south coast of Nuussuaq between GRO#3 and Sikillingi (Fig. 2). Subsequent geochemical analyses of the volcanic rocks demonstrate that there is a stratigraphic continuity between the oldest part of the volcanic succession around Marraat and the slightly younger parts east of the Kuugannguaq–Qunnilik fault shown by Pedersen *et al.* (1993).

Two geological maps at scale 1:100 000 covering the southern, central and eastern parts of Disko were compiled photogrammetrically in 1998 (69 V1.S Uiffaq and 69 V2.N Pingu), integrating results of earlier field work and an extensive geochemical analysis programme. The maps cover plateau lavas and underlying sediments and will be used in the interpretation of both surface and deep structures in the Nuussuaq Basin.

Structural compilation of Svartenhuk Halvø

After interpretation of reflection seismic data acquired in 1995 in Disko Bugt, Vaigat and Uummannaq Fjord and modelling of all available gravity data had been completed, new structural models for the Nuussuaq Basin were prepared (Chalmers *et al.* 1998, 1999). The maps compiled do not, however, extend north of Ubekendt Ejland due to lack of seismic data. In order to complete the studies by Chalmers *et al.* an analysis of Svartenhuk Halvø was initiated by J.G. Larsen and T.C.R. Pulvertaft. Like Nuussuaq, outer Svartenhuk Halvø consists of Cretaceous – lower Paleocene sediments overlain by upper Paleocene basalts.

The structural pattern in this area is dominated by NW–SE trending extensional faults and monoclinal flexure zones, and the general south-westerly dips are the consequence of rotation of fault blocks. Both extensional fault zones and flexure zones show left-lateral offset at WNW–ESE transfer faults along which actual displacements are right-lateral. Since all these structures affect upper Paleocene basalts, they are Eocene or younger in age. Fault movements along the boundary fault system separating the basin in the south-west from the elevated basement area in the north-east are more complex, and there is evidence along the boundary fault system for alternating phases of subsidence and uplift that started in the Cretaceous and continued until after the extrusion of the Paleocene basalts (J.G. Larsen and T.C.R. Pulvertaft, unpublished data).

Release of data from the GRO#3 well

As a consequence of the relinquishment of the grønArctic licence, data from the GRO#3 well have been released and a well-information package comprising reports and wireline logs is available from the Survey, which also has available for distribution an eight volume information package including numerous papers and reports (also on GRO#3) from the Disko – Nuussuaq – Svartenhuk Halvø region.

The GRO#3 well was drilled in August–September 1996 to a total depth of 2996.2 m (Christiansen *et al.* 1997). The well was logged by the Schlumberger Logging Company which prepared a full suite of nuclear, acoustic and resistivity logs and a vertical seismic profile (VSP).

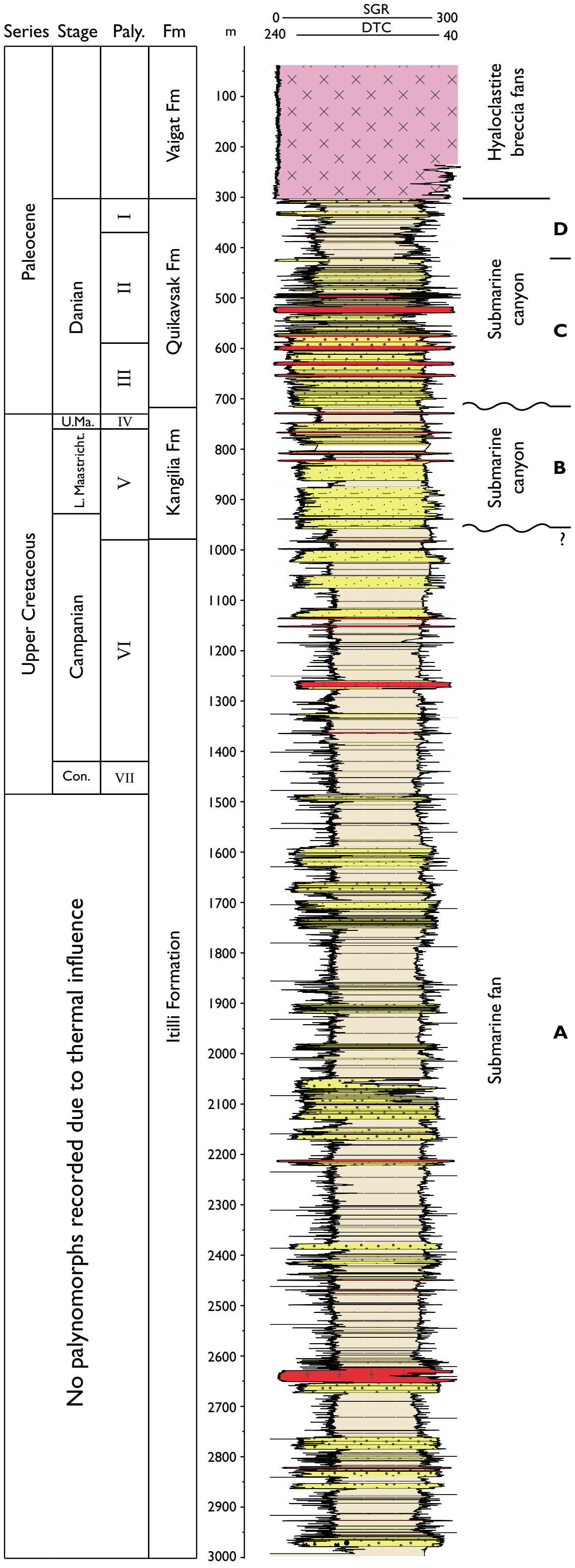
A lithological and petrophysical evaluation of the well has been undertaken by the Survey (Kristensen & Dam 1997), and the organic geochemistry and the biostratigraphy have been described by Bojesen-Koefoed *et al.* (1997) and Nøhr-Hansen (1997), respectively.

The uppermost 303 m in the well consist of Paleocene volcanics. The underlying sedimentary succession consists of sandstone, mudstone/shale, dykes and sills, and tuff mixed with shale (Fig. 5). A total of 39 igneous intrusions with a cumulative thickness of about 145 m were intersected in the well. By correlating the log pattern and the lithological description of the sedimentary succession with palynostratigraphic data by Nøhr-Hansen (1997) and outcrop data, the drilled succession in the GRO#3 well has provisionally been divided into four units, A–D, that correlate with known lithostratigraphic units from nearby exposures and shallow borehole cores.

Stratigraphic units

Unit A is more than 2 km thick (Fig. 5). The uppermost 500 m of the unit has a Coniacian to late Campanian age (Nøhr-Hansen 1997), whereas the lowermost 1500 m cannot be palynostratigraphically dated due to thermal alteration. Unit A comprises mudstone, interbedded sandstone and mudstone, and sandstone. The log pattern of this unit is 'blocky' showing no overall coarsening- or fining-upward cycles. The sandstone intervals are from a few metres to more than 50 m thick. The gamma-ray log pattern suggests that the sandstones mostly have sharp basal contacts and that several of the sandstones have an overall fining-upward trend.

Unit A is lithostratigraphically correlated with the formation exposed in the nearby Itilli valley (Fig. 2; Kristensen & Dam 1997). The outcrops show lithological characteristics similar to those interpreted in Unit A in the GRO#3 well (cf. Itilli succession of Dam & Sønderholm 1994). The exposed sandstones were deposited from turbidite flows in slope channels. The channel sandstones rest on an eroded surface and consist of amalgamated sandstone beds that occur in successions up to 50 m thick. Generally, the turbidite channel deposits show an overall fining-upward trend similar to that seen in the sandstone intervals in GRO#3



Legend

▨	Hyaloclastite
🟥	Igneous intrusive
▭	Mudstone
▨	Interbedded mudstone and sandstone
▨	Sandstone

Fig. 5. Log of the GRO#3 well.

and a similar depositional environment is suggested for Unit A.

Unit B is a 241 m thick sandstone-dominated interval with an early to late Maastrichtian age (Fig. 5; cf. Kristensen & Dam 1997; Nøhr-Hansen 1997). It consists of three sharp-based sandstone intervals separated by mudstones. The sandstone- and mudstone-dominated intervals show a blocky pattern on the log. This unit can be correlated palynostratigraphically with the Kangilia Formation on the north coast of Nuussuaq and at Ataata Kuua on the south coast. At both these localities the formation has an erosional unconformity at the base and is succeeded by submarine canyon sandstones and conglomerates followed by marine mudstones. Outcrop observations from the north and south coast of Nuussuaq suggest that an unconformity is present at the base of Unit B and that the sandstones were deposited in turbidite slope channels and the mudstone in interchannel areas.

Units C and D together are 415 m thick and consist of a major fining-upward succession (Fig. 5). The units have a Danian age (Nøhr-Hansen 1997). The uppermost part of Units C–D can be correlated both lithostratigraphically and palynostratigraphically with the Quikavsak Member (cf. Dam & Sønderholm 1994) in GANE#1 drilled 4 km east-north-east of GRO#3 (Kristensen & Dam 1997; Nøhr-Hansen 1997). The lower part of the GANE#1 core that can be correlated with Unit C consists of a thick succession of amalgamated, thickly bedded, coarse- to very coarse-grained sandstone beds, deposited from sand-rich turbulent flows in a canyon environment (Dam 1996). Unit D is heterolithic; in the GANE#1 core the unit consists of mudstone, interbedded muddy sandstone, thinly interbedded sandstone and mudstone, amalgamated sandstone and chaotic beds. Volcanic fragments occur in the upper part of the core. This succession probably constitutes an upper canyon fill deposited mainly from low- and high-density turbidity currents, debris flows and slumps.

Petrophysical evaluation

A petrophysical evaluation of the GRO#3 logs indicates that the sandstone intervals have low to fair porosities (5–15%). In particular the sandstones in the uppermost part of the well (the interval from 423 m to 718 m is equivalent to the upper part of the Quikavsak Member; cf. Dam & Sønderholm 1998) are considered to be potential reservoir rocks (Kristensen & Dam 1997).

The Quikavsak Member sandstones in the GRO#3 well are characterised by deep drilling mud invasion, presumably due to the use of relatively high mud weight in this interval. Invasion is, however, to be expected in a reservoir characterised by low to fair porosities. The Density-Neutron log combination indicates either low gas saturation or that the hydrocarbon-bearing intervals contain oil as well as minor amounts of free gas. According to a quantitative interpretation of the logs acquired in the well, the Quikavsak Member exhibits hydrocarbon saturations up to 50% (high case), but these saturation estimates are subject to several uncertainties. The main uncertainty concerns the resistivity of the formation water (R_w), because the fluid samples available are contaminated by drilling mud filtrate and hence representative R_w values cannot be determined. The invasion of drilling mud filtrate into the formation is another source of uncertainty. Unfortunately, the Quikavsak Member was cased prior to the drilling of the main hole. In the remaining part of the well, the log interpretation shows the presence of hydrocarbons in several, but relatively thin, intervals. Some of these intervals have been tested, but only very low amounts of fluids were recovered.

Organic geochemistry and thermal maturity

GRO#3 is the first deep exploration well drilled onshore West Greenland. Data from the well are therefore very important for the assessment of the exploration potential of the Nuussuaq Basin, because they provide much better information on thermal maturity gradients than previous studies which were only based on outcrop samples or shallow cores.

The geochemical data from GRO#3 confirm the generally high organic content throughout the succession of Upper Cretaceous and Paleocene mudstones (Fig. 6; TOC: 1.15–6.55%, average: 4.46%). The mudstones have moderate to high sulphur values (TS: 0.52%–3.83%, average: 1.83%) that are typical for marine mudstones with significant input of terrestrially derived organic matter.

A well-developed, depth-dependent maturity-trend is observed throughout the penetrated succession (see T_{max} and R_o in Fig. 6); this gradient is also expressed by a number of biological marker ratios in the shallower part of the succession (Bojesen-Koefoed *et al.* 1997). The maturity trend is remarkably regular and shows no sign of anomalies caused by intrusions, hydrothermal activity or changes in gradient across possible uncon-

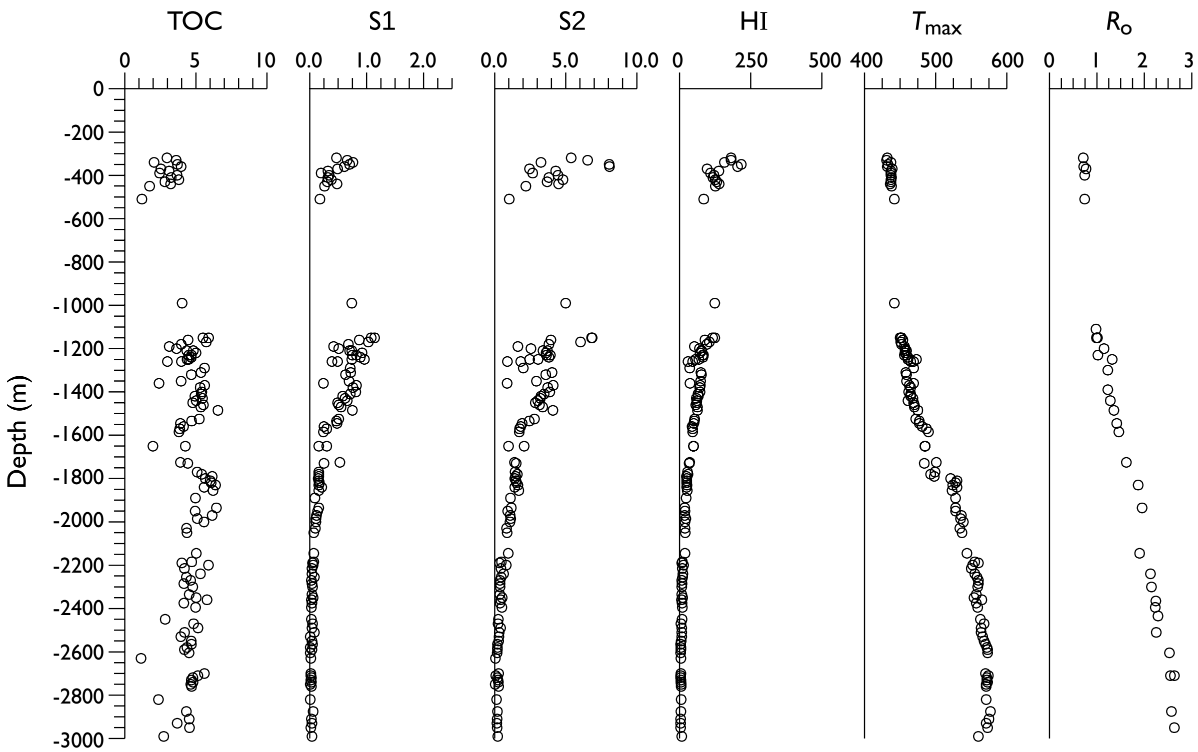


Fig. 6. Organic geochemical and thermal maturity parameters versus depth for the GRO#3 well. **TOC**: Total organic carbon (%). **S1**: Hydrocarbons already present in the rock (mg HC/g rock). **S2**: Hydrocarbons generated during pyrolysis (mg HC/rock). **HI**: Hydrogen index. $\boldsymbol{T_{max}}$: Maturity parameter from Rock-Eval pyrolysis (°C). $\boldsymbol{R_o}$: Vitrinite reflectance (%).

firmities. The many different maturity data generally suggest that the base of the oil window is at a depth of *c.* 1.5 km and that the base of the oil preservation zone is at a depth of *c.* 2.2 km. This is consistent with the previous estimate of an overlying succession that reached 1900 m above sea level prior to erosion (Bojesen-Koefoed *et al.* 1997).

Detailed gas chromatography and gas chromatography/mass spectrometry studies from the upper part of the well have demonstrated a remarkable similarity in geochemistry between the mudstones from the interval from 320 m to 510 m in the GRO#3 well and the Marraat oil type (see details in Bojesen-Koefoed *et al.* 1997, 1999). The high concentration of distinct angiosperm-derived biomarkers in particular, suggest that this interval of Danian age is the source rock for the widely distributed Marraat oil type.

Basin modelling

The thermal maturity data from GRO#3 have been very important for a recently completed modelling project that integrates all geological information available from the Nuussuaq Basin (Mathiesen 1998). By using a basin modelling approach that is constrained by thermal maturity data and new apatite fission track data it has been possible to outline consistent burial, uplift and erosion models for the Nuussuaq Basin. Due to a limited number of apatite fission track data there are still some uncertainties with respect to the timing of uplift and erosion. This has strong implications for exploration, and the question of preservation of once-trapped hydrocarbons below the volcanic rocks is one of the remaining risk factors in the area.

Offshore West Greenland

The offshore areas of West Greenland were the scene of increased exploration activities in the summer of 1998.

The Statoil group continued their work in the Fylla licence area with acquisition of a site survey in two areas. A total of 442 km shallow seismic data and 64 gravity cores (0.8 m to 3 m long) were obtained. Statoil used the Fugro-Geoteam vessel *Geo-Scanner* for this purpose. After completion of the site survey, Fugro-Geoteam

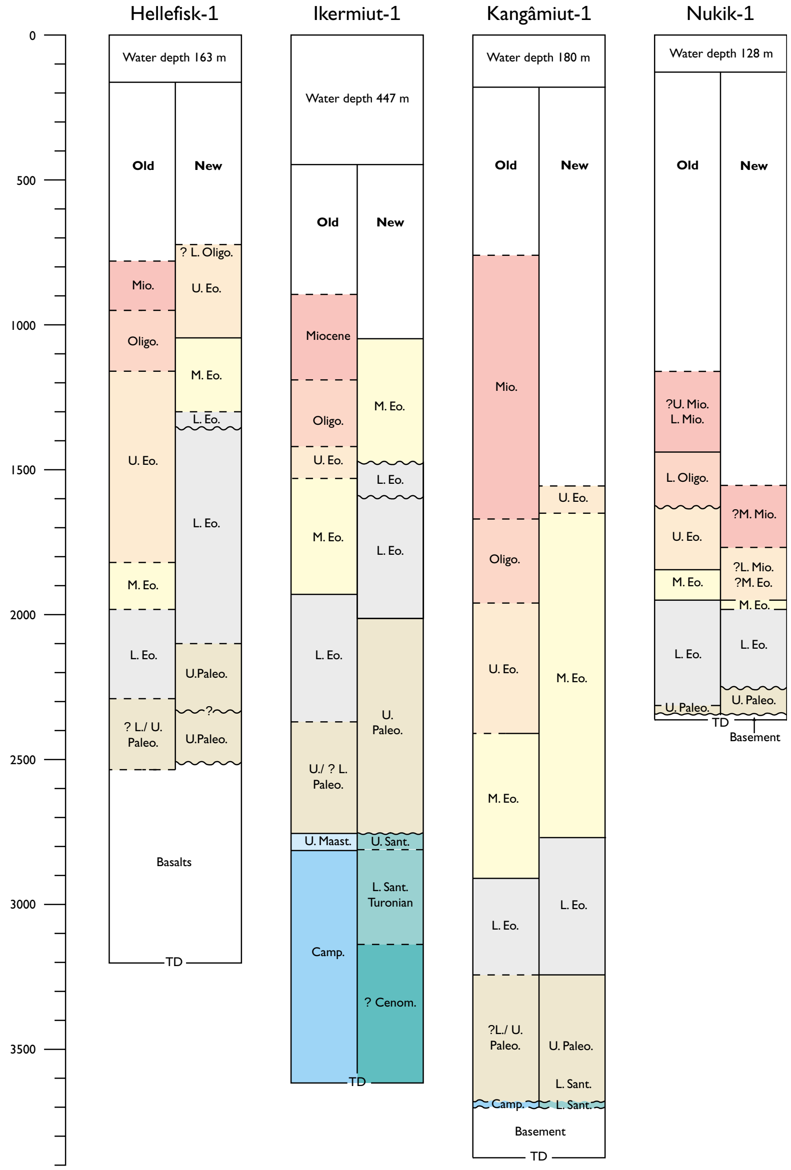


Fig. 7. Summary of the new palynostratigraphy offshore West Greenland based on four wells. Modified from Nøhr-Hansen (1998).

acquired 3126 km of non-exclusive multichannel seismic data just north and south of the Fylla licence area. In addition a project on a non-exclusive basis involving reprocessing of older seismic data has been initiated by Fugro-Geoteam and Danpec.

Nunaoil A/S continued its acquisition of non-exclusive seismic data off West Greenland, mainly east and north of the Sisimiut-West licence area. A total of 1610 km were acquired using the Danish Naval vessel *Thetis*. The Phillips group also used *Thetis* to acquire a few lines in their new Sisimiut-West licence area.

The Survey continued work on seismic and well data from offshore West Greenland. Seismic interpretation focused very much on the area west of Disko where bright spots occur at top basalt level and at a horizon about 200 m above the basalts (Skaarup & Chalmers 1998; Skaarup *et al.* in press). Amplitude Versus Offset (AVO) studies of two seismic lines show that the bright spots exhibit very strong anomalies that could indicate the presence of large quantities of hydrocarbons.

A new palynostratigraphy based on a comprehensive reinvestigation of material from four of the offshore wells from the 1970s has been reported by Nøhr-Hansen (1998). Significant changes have been made relative to earlier stratigraphic interpretations, especially in the upper parts of the wells, which are all shown to be of an older stratigraphic age than previously suggested (Fig. 7). A major hiatus spanning the uppermost Cretaceous to the Lower Paleocene has been recorded from both the Ikermiut-1 and Kangâmiut-1 wells and several hiatuses have been recorded within the Palaeogene in all wells. These changes have significant consequences for correlation of seismic units, sequence stratigraphy and interpretation of depositional systems. The subsidence history has also been considerably revised, which will affect basin modelling results concerning depth to, and timing of, hydrocarbon generation.

Future Survey work in West Greenland

In order to support and stimulate ongoing and future exploration in West Greenland a number of new research projects have been initiated at the Survey and several current studies will continue. In preparation for the coming licensing round and the re-established open door procedure, an exploration assessment of West Greenland will be undertaken. This work will include interpretation of all available seismic data offshore West Greenland, new organic geochemical studies of material from the offshore wells, description of new play types, leads and prospects, and ranking of blocks. A preliminary analysis of available data on seabed geology and dynamics of Neogene–Quaternary depositional systems will also be started in order to identify potential geohazards that could be critical for exploration and production.

Funding has been granted for an Energy Research Project (EFP) to investigate the depositional systems and hydrocarbon prospectivity of the Palaeogene succession offshore southern West Greenland. An earlier regional interpretation of seismic data revealed the existence of complex highstand and lowstand fan systems that could be stratigraphic traps for hydrocarbons. New seismic interpretation will be supplemented by lithostratigraphic, biostratigraphic and sequence stratigraphic interpretations of data from the five wells drilled in the 1970s. Funding has also been granted from EFP and the Government of Greenland for acquisition of high resolution multichannel seismic data in the fjords north and south of Nuussuaq (actual survey planned for the summer of the year 2000). These data should give a better understanding of the structure and exploration potential of the Nuussuaq Basin both onshore and offshore.

Studies of Cretaceous–Palaeogene source rocks and oils continue (Nytoft *et al.* in press). The extensive sample material from West Greenland (and Ellesmere Island in the Canadian Arctic) is also being used in a new EFP project 'Petroleum source potential of terrigenous source rocks'. The petroleum source potential will be evalued by detailed organic geochemical and petrographic analyses as well as by kinetic studies. Hydrous pyrolysis experiments are being carried out on a series of samples, and maturation curves will be prepared. The results are expected to contribute to the clarification of questions regarding the critical factors such as generation characteristics, gas/oil ratios and the relative importance of angiosperm/gymnosperm organic matter.

Field work in 1999 will focus on Svartenhuk Halvø with additional 'oil hunting' along the coasts and sampling for palaeomagnetic studies. Critical localities of importance for the structural conclusions of J.G. Larsen and T.C.R. Pulvertaft will be revisited. Sedimentological and stratigraphic studies will cover both non-marine and marine sections focusing on Upper Cretaceous and Paleocene submarine channel deposits and their possible correlation with similar deposits on Nuussuaq.

Acknowledgements

Funding of the Survey's field work in the Disko–Nuussuaq region and subsequent analytical work was provided by the Government of Greenland, Bureau of Minerals and Petroleum. Mobilisation of the field camps took place from Arktisk Station, Godhavn with the help of the ship *Maja S.* Finn Steffens and his crew are thanked for good seamanship and much practical help.

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Observations on the Quaternary geology around Nioghalvfjerdsfjorden, eastern North Greenland

Ole Bennike and *Anker Weidick*

In North and North-East Greenland, several of the outlet glaciers from the Inland Ice have long, floating tongues (Higgins 1991). Nioghalvfjerdsfjorden (Fig. 1) is today occupied by a floating outlet glacier that is about 60 km long, and the fjord is surrounded by dissected plateaux with broad valleys (Thomsen *et al.* 1997). The offshore shelf to the east of Nioghalvfjerdsfjorden is unusually broad, up to 300 km wide (Cherkis & Vogt 1994), and recently small low islands were discovered on the western part of this shelf (G. Budeus and T.I.H. Andersson, personal communications 1998). Quaternary deposits are widespread around Nioghalvfjerdsfjorden and include glacial, glaciofluvial, marine, deltaic and ice lake deposits. Ice margin features such as kame deposits and moraines are also common (Davies 1972). The glaciation limit increases from 200 m a.s.l. over the eastern coastal islands to 1000 m in the inland areas; local ice caps and valley glaciers are common in the region, although the mean annual precipitation is only about 200 mm per year. Most of the sea in the area is covered by permanent sea ice, with pack ice further east, but open water is present in late summer in some fjords north of Nioghalvfjerdsfjorden, and in the Nordøstvandet polynia.

Earlier information on the Quaternary geology of the region north of Nioghalvfjerdsfjorden has been given by Davies (1963), Funder & Hjort (1980) and Hjort (1997); the region south of Nioghalvfjerdsfjorden has been reported on by Landvik (1994) and Weidick *et al.* (1996). During field work in 1987, some pieces of drift wood (undated) and an occurrence of marine shells were located at Blåsø (Bennike 1987). In connection with the glaciological work in 1996 samples of marine shells and driftwood were collected between the 'Midgårdsormen' base camp and Blåsø. In 1997 Quaternary field work was conducted around Blåsø, on southern Hovgaard Ø, on eastern Lambert Land and on Norske Øer. Supplementary Quaternary field work was undertaken in 1998 on Søndre Mellemland and on Île de France (Fig. 1).

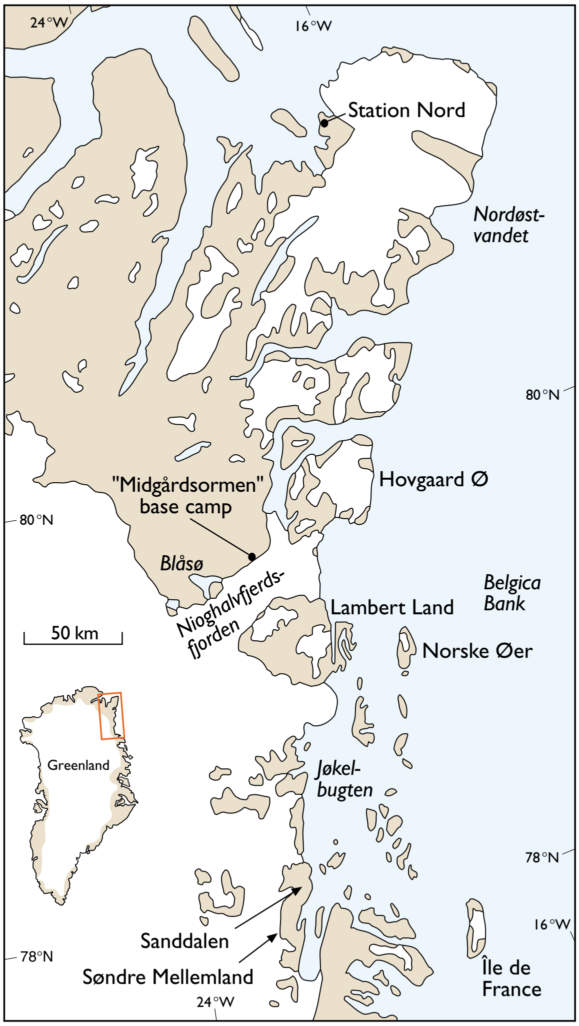

Fig. 1. Map of northern North-East and eastern North Greenland showing localities mentioned in the text.

Methods

Samples were collected along a transect between Blåsø in the inland area and the outer coast, and 48 samples of shells, driftwood, plant remains and bones have so far been radiocarbon dated. Special attention was given to collecting material that could shed light on the timing of the deglaciation, and on the timing of the onset of the neoglaciation. Most samples were dated by accelerator mass spectrometry (AMS) radiocarbon dating, but some samples were dated by conventional radiocarbon dating. All dates have been calibrated according to dendrochronology, and in this article only the calibrated dates are discussed.

Results

Heavily abraded bedrock with perched boulders and glacial striae indicative of former ice movement towards the east are found on Norske Øer and on eastern Lambert Land at the outer coast (Fig. 1). The freshness of these features point to a Late Weichselian age, and a subsequent major recession of the Inland Ice can also account for the Holocene glacio-isostatic rebound. Thus the marine limit was found to decrease from *c.* 65 m a.s.l. at the outer coast to *c.* 40 m a.s.l. in the inland areas. The marine limit is dated to the early Holocene, and since the eustatic rise of sea level since the early Holocene amounts to *c.* 50 m (Fairbanks 1989), the isostatic rise must be at least 100 m. Several of the radiocarbon dates obtained pertain to the timing of the deglaciation of Nioghalvfjerdsfjorden. The oldest date obtained near the outer coast is *c.* 9.7 cal. ka BP (calibrated kilo years before present), which is more than 1000 years younger than in areas further to the south and north. This indicates that the eastern margin of the Greenland ice sheet was still located on the shelf in the early Holocene and perhaps buffered against the shallow part of Belgica Bank.

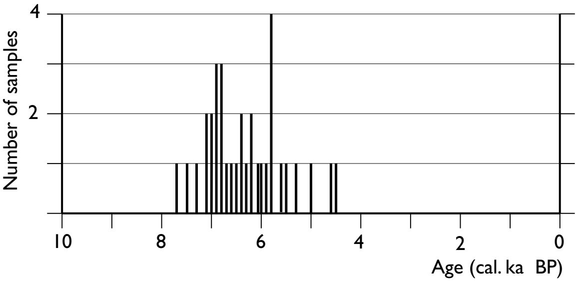

Fig. 2. Diagram showing the temporal distribution of radiocarbon dates from the inner part of Nioghalvfjerdsfjorden. Only datings of mollusc shells, bones of marine mammals and driftwood are included.

The oldest date obtained near Blåsø is *c.* 7.7 ka BP (Fig. 2), which indicates that the deglaciation of the fjord took about 2000 years, corresponding to a recession rate of 30–40 m/year. During the deglaciation, moraine ridges were formed east of Blåsø, and a giant ice-dammed lake occupied some of the valleys northeast of Blåsø.

After deglaciation, molluscs and marine mammals were able to live in Nioghalvfjerdsfjorden, and driftwood could enter the fjord. Twenty shell samples, nine samples of driftwood, five bones of seals and bone of a whale, collected on raised beaches, on raised marine deposits and along the shore of Blåsø, have been dated (Figs 2, 3); these yielded ages between *c.* 7.7 ka BP and 4.5 ka BP. The distribution of dates shows that the fjord was not glaciated during this period in the middle

Fig. 3. **A**: Fragments of two ribs of a whale, probably Greenland right whale (*Balaena mysticetus*), found on raised beaches. Matchbox for scale. **B**: Thigh bone of a seal, probably ringed seal (*Pusa hispida*), and shells of *Mya truncata*, found on raised marine deposits. Pencil for scale. Both found near Blåsø in the inner part of Nioghalvfjerdsfjorden.

Holocene. Molluscs and ringed seals may have lived in the fjord during periods of permanent sea ice, whereas driftwood and whales could only enter the fjord during periods of open water. The driftwood and whale dates are restricted to the period 7.0–5.4 ka BP, and it is possible that this period was preceded and followed by periods when the fjord was covered by sea ice throughout the year. On Norske Øer, where the presence of permanent sea ice hinders the formation of beach ridges at the present time, a series of raised beach ridges are found that were presumably formed during the middle Holocene. The mollusc fauna during the middle Holocene included the bivalves *Macoma calcera* and *Serripes groenlandicus* that have not previously been reported from Holocene deposits this far north in East Greenland, and it is possible that these species were only able to live here during the middle Holocene warmth optimum. Fruits of two species of southern extra-limital plants, *Empetrum nigrum* and *Potamogeton filiformis*, that were recovered from foreset beds in a raised delta near Blåsø and dated to *c.* 5.1 ka BP, are also indicative of summer temperatures higher than the present in the middle Holocene. In a small lake near Blåsø clay gyttja is overlain by clay at 60 cm below the lake bottom. This lithological change is somewhat younger than 4 ka BP, and it appears to post-date the onset of the neoglaciation; since then Nioghalvfjerdsfjorden has been occupied continuously by a floating glacier. The neoglaciation culminated during the Little Ice Age, probably at around AD 1900, after which a slight thinning and recession has occurred. Fresh strandlines along Blåsø show that during the Little Ice Age the lake was dammed with a water level about 1 m higher than at present.

Jøkelbugten

Observations on the Quaternary deposits in Søndre Mellemland were conducted from one field camp in Sanddalen, and an unnamed island in Jøkelbugten was visited during two short ground stops. The first radiocarbon dates now available show that Jøkelbugten was not deglaciated until well into the Holocene. Thus the oldest shell date from Søndre Mellemland is *c.* 8.1 ka BP. West of Sanddalen an area of around 15 km^2 with ice cored moraines is found. Scattered shells and shell fragments of *Hiatella arctica, Mya truncata* and *Astarte borealis* are found on the terrain surface up to 200 m above sea level, and a single radiocarbon dating has yielded a mid-Holocene age. This indicates that the area was a fjord arm in the middle Holocene, and that the ice cored moraines were formed during the neoglacial. Fresh moraines that presumably date from the Little Ice Age are found adjacent to the margin of the Greenland Inland Ice, which indicates that the neoglacial maximum in this area predates the Little Ice Age.

Île de France

Sediments assigned a Late Pliocene or Early Pleistocene age were reported from this island by Landvik (1994). We found rich, though not very diverse, marine macrofaunas in sections near the northern tip of the island (Fig. 4). Preliminary identifications show that the fauna includes *Spirorbis* sp., Decapoda indet., *Boreocingula* sp., *Trichotropis bicarinata, Euspira* cf. *E. pallida, Cryptonatica* aff. *C. affinis, Trophon* cf. *T. truncatus, Neptunea* sp., *Admete* sp., *Oenopota* sp., *Nucula*

Fig. 4. General views of exposures of Pliocene sediments near the northern tip of Île de France. Height of sections around 40 m, with the top *c.* 80 m above sea level.

(Lamellinucula) cf. *N. (L.) jeffreysi, Nuculana pernula, Portlandia arctica, Yoldiella intermedia, Yoldiella* sp., *Astarte borealis, A. montagui, Astarte domburgensis, Astarte alaskensis, Arctinula greenlandica, Clinocardium ciliatum, Serripes groenlandicus, Arctica islandica, Hiatella arctica, Mya truncata* and ?*Terebratula* sp.

Wood remains are fairly common and a few seeds and fruits were also found; the latter include *Picea* cf. *P. mariana* (black spruce), *Menyanthes trifoliata* and *Potamogeton filiformis*. The fauna shows similarities to the older part of the Kap København Formation (Bennike 1989, 1990; Símonarson *et al.* 1998), and to Neogene deposits in North-West Europe, and a Pliocene age is suggested. The marine fauna indicates a shallow shelf environment and a subarctic climate much warmer than that of the present. Further work is in progress on the fauna, flora and chronology of this sequence that appears to be the first Pliocene sequence located in Greenland.

Acknowledgements

Peter Rasmussen and Peter Friis Møller are thanked for excellent field assistance, and Susanne Lassen kindly commented on the text. Radiocarbon dates were made at the Institute of Physics, Aarhus University, Denmark (Jan Heinemeier), at the Tandemlaboratoriet, Uppsala, Sweden (Göran Possnert), and at the National Museum, Copenhagen (Kaare Lund Rasmussen). The project was financially supported by the Commission for Scientific Research in Greenland and the Danish Natural Science Research Council. Hauge Andersson from the Danish Polar Center established the logistic platform for the field work. Anders Warén (Stockholm) and Winfried Hinsch (Kiel) kindly commented on the identification of some mollusc shells from Île de France, and Jeppe Møhl (Copenhagen) identified the bone material.

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Climate change and the Viking-age fjord environment of the Eastern Settlement, South Greenland

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and *surveyors of the Royal Danish Administration for Navigation and Hydrography*

The main objective of the project reported here is to reconstruct late Holocene hydrographic changes in South Greenland fjords and to study the relationship with large-scale atmospheric climate change; in particular to shed light on a possible link between these hydrographic changes and the disappearance of the Norse from Greenland more than five centuries ago. The project (1998–2000) is financially supported by the Danish Natural Science Research Council and the Government of Greenland.

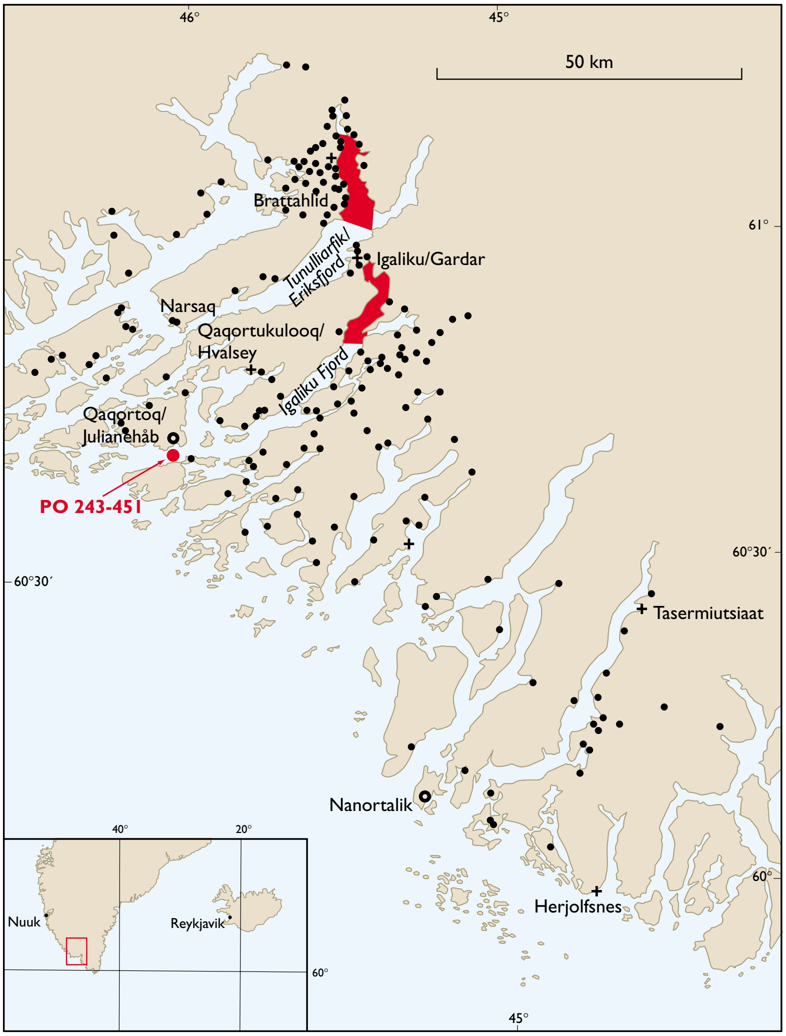

Fig. 1. Map of the Norse Eastern Settlement, with location of the study areas (**red**) in the innermost part of Tunulliarfik and Igaliku Fjord; the present towns of Qaqortoq/Julianehåb and Nanortalik are shown. The location of core PO 243-451 is also indicated. **Black dots** are ruins or sites related to the Norse period. **Crosses** indicate church ruins. The inset map shows the regional setting of the study area, the location of Iceland with the capital Reykjavik. The Inland Ice is not shown.

Geology of Greenland Survey Bulletin 183, 61–67 (1999)

From the ‘Grønlændersaga’ and confirmed by historical and archaeological evidence we know that a Norse colony (for location, see Fig. 1) was founded in South Greenland in AD 985 by Eric the Red and other settlers from Iceland. Despite a large number of studies undertaken onshore in the area of the Eastern Settlement, the ultimate cause for the loss of the settlement almost 500 years later has not yet been determined. Amongst the explanations proposed for the disappearance of the Norse population, researchers have invoked climatic change, decline of shipping trade with Iceland and Europe, raids by European pirates, competition with immigrating Inuits, and disease.

From Mediaeval Icelandic sources we know that after the first period of colonisation, sea ice off south-eastern Greenland had significantly expanded, causing growing problems to Norse shipping between Iceland and Greenland. Numerous indications have been found in the northern hemisphere pointing to severe climate deterioration between about AD 1350 and AD 1850 (Little Ice Age), following the end of the Mediaeval Warm Period or Climatic Optimum (*c.* AD 900–1350). As described by Dansgaard *et al.* (1989), cold climate conditions revealed by the ice core records from central Greenland were characterised by dry and very stormy weather conditions, providing further evidence for adverse sailing conditions. Further evidence for more stormy weather also having affected the coastal areas of Greenland, particularly during the winter months, has recently come from studies carried out in North-East Greenland (Christiansen 1998). Stuiver *et al.* (1995) found in their study of the GISP2 Greenland ice core that Little Ice Age cold conditions prevailed between *c.* AD 1350 and 1800, with the extremes of low temperature dated at AD 1720. They dated the Mediaeval Climatic Optimum peak at AD 975, i.e. close to the time of the Norse ‘landnám’ in South Greenland. It is emphasised here, that due to their location the climate records from the central Greenland ice cores cannot resolve all low-altitude climatic changes of the more maritime domaines of Greenland. As an example, the Greenland Summit ice cores GISP2 and GRIP reveal a remarkably stable Holocene climate compared to the glacial record. However, records from smaller ice caps more exposed to (Arctic) ocean climate at lower altitudes, e.g. Hans Tausen Iskappe, eastern North Greenland, and the Devon and Agassiz ice caps in the Canadian Arctic Archipelago, clearly demonstrate substantial climatic changes within the Holocene.

Until now, however, there was no firm evidence for a causal link between the Little Ice Age climate deterioration and the loss of both the Western and Eastern Settlements. The latter was notably able to survive for several generations after the beginning of the Little Ice Age.

It may be relevant here to note that while modern global average annual temperature has been steadily rising since the beginning of the 1980s, over the last decade a significant cooling trend has been observed in the West Greenland temperature records (Danish Meteorological Institute, unpublished data). In addition, Greenland ice core measurements indicate decreasing temperatures over central Greenland during the last few decades (Dahl-Jensen *et al.* 1998). Thus, northern hemisphere climatic trends can display large regional differences, which may also have applied to the various Little Ice Age stages.

Project concept

With the background information referred to above, it was envisaged that a better understanding of the disappearance of the Norse from the Eastern (and Western) Settlements might be achieved by studying the possible impact of the Little Ice Age on the fjord waters surrounding the settlements. It is evident, that for shipping and food supply these waters have been of crucial importance for the survival of the settlement. Major regional hydrographic changes, such as a more extensive or semi-permanent ice cover, can be assumed to have had major consequences for the fjord flora and fauna, and, therefore, for the standing stocks available for hunting and fishing. Such changes would also have had a negative effect on shipping. In a broader sense, such palaeo-hydrographic studies will add to our knowledge of the regional oceanographic impact induced by large-scale climatic change.

The project was launched through the initiative of the Geological Survey of Denmark and Greenland (GEUS) in co-operation with the Research Center for Marine Geosciences (GEOMAR) in Kiel, Germany. Close collaboration with the National Museum of Denmark in Copenhagen and Roskilde, and the National Museum and Archive of Greenland in Nuuk was obvious. A collection of sediment cores from the bottom of the fjords was considered to be essential. In order to locate the most suitable locations for coring, a shallow seismic survey was a pre-requisite. Use of the relevant acoustic techniques also included deep-tow side-scan sonar in order to be able to trace possible underwater cultural heritage sites such as shipwrecks, lost cargo, constructions or other items.

Deployment of deep-tow side-scan sonar equipment at 200–300 m water depth, and more generally, navigation by a large research vessel, can only be undertaken when basic bathymetric data are available. Since this information was not available for the fjords under investigation, the involvement of the Royal Danish Administration for Navigation and Hydrography (Farvandsvæsenet) was necessary for carrying out the project. Finally, the deployment of a Remote Operated Vehicle (ROV) was foreseen as part of the work at sea to investigate possible acoustic targets.

Shipboard studies with RV *Poseidon*

The research cruise with RV *Poseidon* (Cruise 243) was carried out between 24 August and 10 September, 1998, with Reykjavik as the logistic port for the start and end of the cruise. Scientists from GEUS, GEOMAR, the Greenland National Museum, the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, the Norwegian University of Science and Technology, Trondheim, the University of Iceland, and from the Southampton Oceanography Centre, United Kingdom, were involved. On transit to and from South Greenland gale-force winds were encountered, which resulted in delays of about 24 hours both ways.

Upon arrival in the study area off Julianehåb, on 29 August, a rendezvous was arranged with the two hydrographic survey vessels of the Royal Danish Administration of Navigation and Hydrography, during which the newly acquired results from the bathymetric mapping of the study areas (Fig. 1) were handed over by the commanding officers of the survey vessels to the Master of RV *Poseidon*. In addition, useful information on relevant navigational aspects was received, and RV *Poseidon* was escorted by the survey vessels to its working area at the head of Igaliku Fjord. During the entire survey

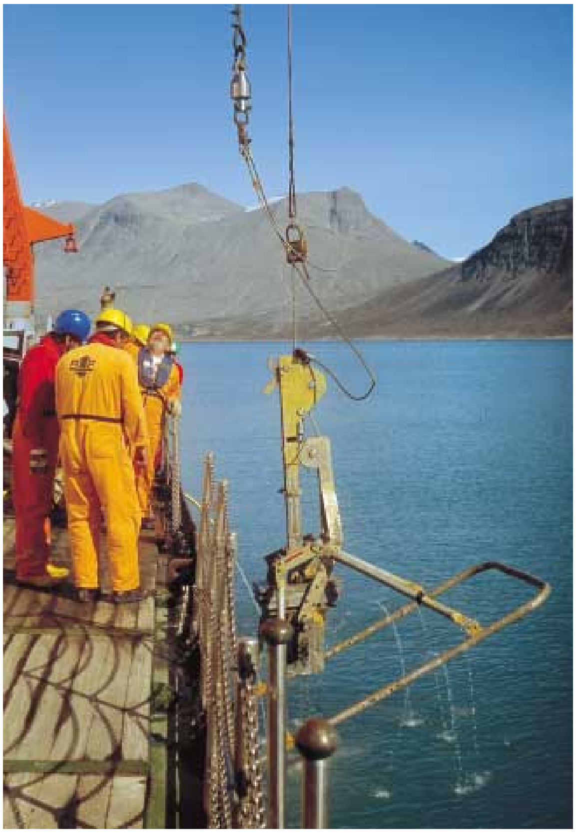

Fig. 2. Retrieval of a box core during sediment sampling operations in Igaliku Fjord.

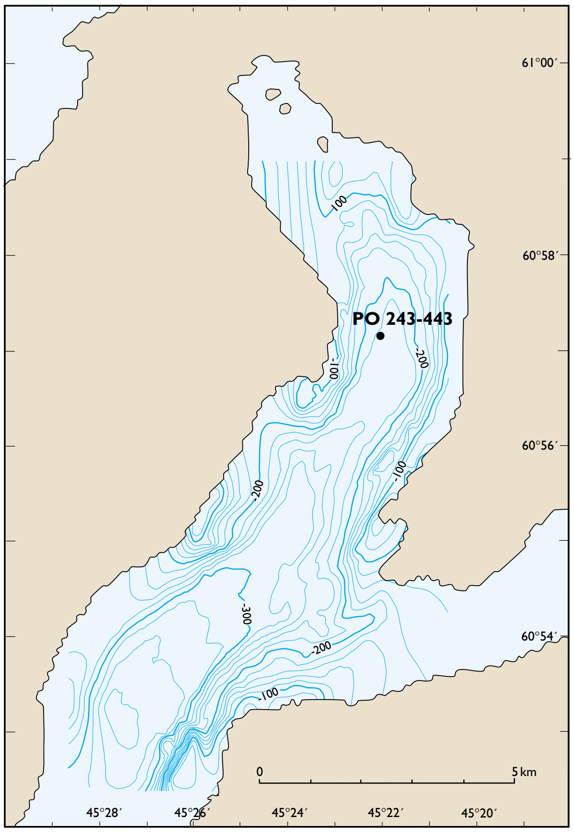

Fig. 3. Bathymetry of the innermost part of Igaliku Fjord obtained with the ELAC multi-beam bottom charting system. The site of core PO 243-443 is shown. For location see Fig. 1.

period favourable weather conditions prevailed (Fig. 2), and ice conditions in Tunulliarfik did not adversely affect the progress of the work.

Both in Igaliku Fjord and in Tunulliarfik a combination of side-scan sonar, hull-mounted ELAC multi-beam bottom charting system, hull-mounted 18 kHz echo-sounder, and a towed, high-resolution CHIRP sub-bottom profiler system were used. In most parts of the survey areas a deep-tow EG & G (59 kHz) side-scan sonar system (Kiel University, Germany) was deployed, but in the shallow coastal zone (< 10 m water depth), which was surveyed by rubber boat, a 100 kHz Klein side-scan sonar driven by batteries was used. Upon completion of the acoustic survey, several objects detected by side-scan sonar, and some additional sites, were investigated by the Remote Operated Vehicle.

In order to obtain sediment samples with an undisturbed surface, a Reineck box corer (Fig. 2) and a 6 m long gravity corer were deployed. With the newly acquired acoustic sub-bottom information it can be concluded that the seabed in both fjords is nearly everywhere characterised by the presence of mass flow and turbidite deposits. Only a few sites were found suitable for coring with the aim of collecting sediments for high resolution palaeo-hydrographic studies. In addition to a number of box cores, a total of seven gravity cores were collected in Igaliku Fjord, and four gravity cores were obtained from Tunulliarfik. An additional gravity core was taken off Qaqortoq/Julianehåb (Fig. 1). Two gravity cores, one from the Igaliku Fjord study area (Fig. 3), and one at the entrance to the fjord near Julianehåb, proved to be of good quality, and were selected for further laboratory analyses.

Post-cruise laboratory analyses

Immediately after the cruise, samples taken from the box cores were transported to the Risø National Laboratory for ^{210}Pb and ^{137}Cs measurements in order to determine recent (last 150 years) accumulation rates. The samples were also analysed for their general geochemical composition. A number of box and gravity cores were measured for magnetic susceptibility, and palaeomagnetic measurements were carried out on the two suitable gravity cores. The latter cores were also subsampled for high resolution geochemical studies (Risø National Laboratory, Denmark). In addition, several horizons were selected for AMS ^{14}C datings to be carried out at the Aarhus University, Denmark dating facility (J. Heinemeier).

Detailed microfossil studies will be undertaken in 1999, in part within the framework of a Ph.D. study to be carried out at the Geological Survey of Denmark and Greenland in Copenhagen and financed by the special North Atlantic Research Program of the Danish Research Agency.

Preliminary results

Coastal drowning

Various indications show that after mid-Holocene times the initial glacio-isostatic rebound of Greenland was followed by increased subsidence, resulting in a relative sea-level rise (e.g. Rasch & Fog Jensen 1997). This subsidence is well documented by the semi-inundation of the Norse graveyard of Herjolfsnes, about 100 km to the south-east of the study area (Fig. 1), and the drowning of Inuit ruins of late Holocene age.

During our shallow water side-scan sonar survey in Tunulliarfik off Brattahlid, the site where Eric the Red settled, a drowned beach was recorded (Fig. 4). After correction for the tidal factor, the level of this drowned beach was shown to be 3 to 4 m below mean sea level. Although no material could be sampled for dating, an age not much in excess of 1000 years BP is envisaged. This is based on the results of the dating of a desiccation horizon at about 9 m below sea level in a core from Narsaq harbour, 30 km to the south-west (Fig. 1). The age of this horizon is 3080 ^{14}C years BP (A. Weidick, personal communication 1999), indicating a relative sea level stand at that time of at least 10 m below the present level. Thus, it is concluded, that the average late Holocene relative sea-level rise is in the order of about (at least) 3 m per 1000 years. This implies that during the 500 years of the Norse settlement era large areas of the fertile lowlands along the fjords were drowned. For example, at the drowned beach zone off Brattahlid (see Figs 1, 4), the relative sea-level rise probably resulted in coastal regression over a distance of more than 100 m for the last *c.* 1000 years. In particular, off the former episcopal residence of Gardar at the northernmost end of Igaliku Fjord, where at present large areas of the fjord are less than 5 m deep, a gradual loss of useful land areas due to the relatively fast sea-level rise must have had a destructive effect on the farming and (grass) cultivation potential of the successive Norse generations in the area.

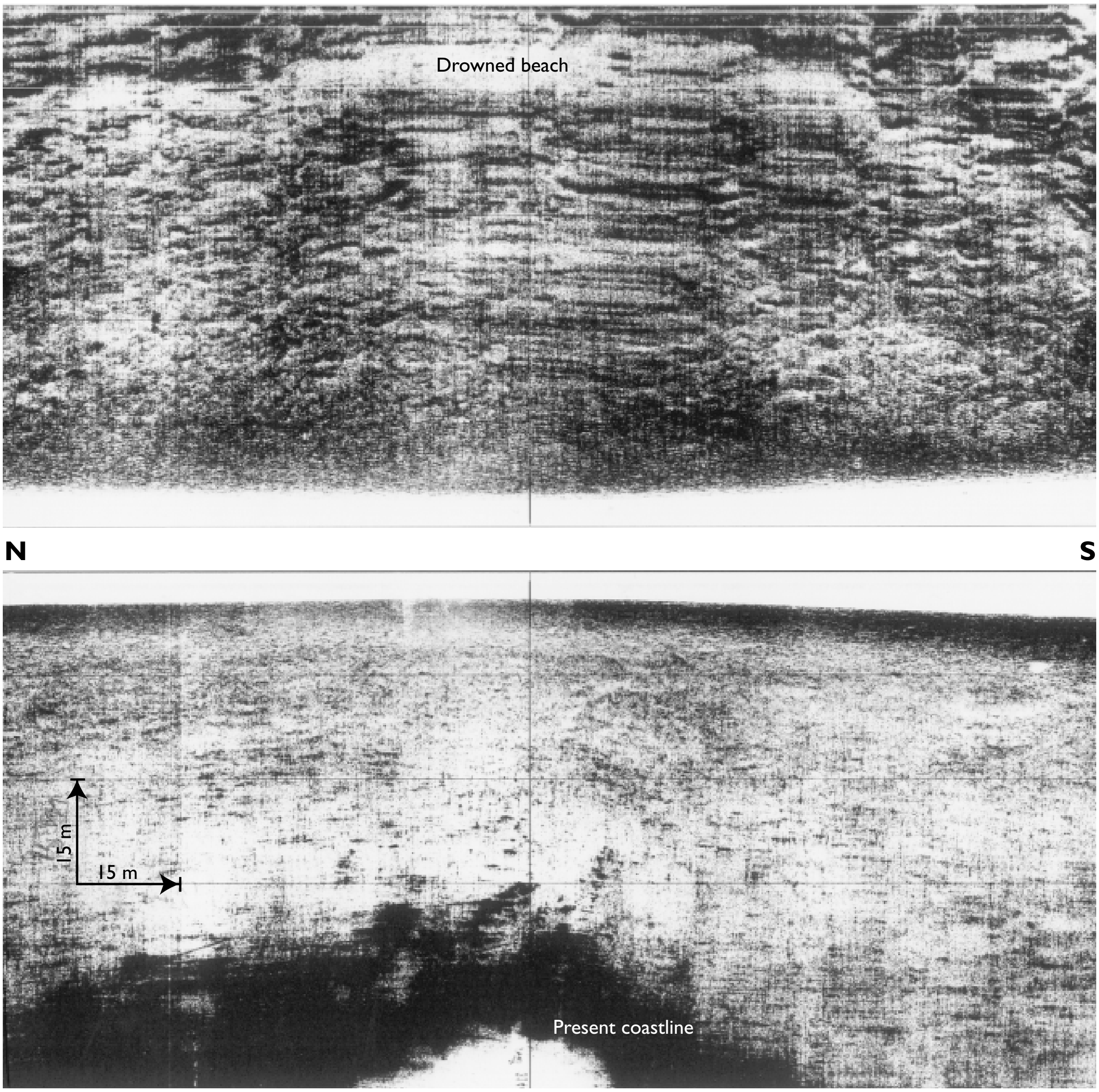

Fig. 4. Side-scan sonar record obtained on a coast-parallel track in shallow waters off Brattahlid. The record shows a drowned beach (white band) at 3–4 m below present mean sea level, at about 110 m distance from the present coastline.

Regional submarine sedimentary disturbances

As outlined above, the subbottom profiler information from most parts of Tunulliarfik and Igaliku Fjord indicates the widespread occurrence of downslope sediment transport processes. Consequently, sediments from the deeper parts of the fjords frequently contain coarser-grained (sand, gravel) material derived from debris flow and turbidity current processes. Additional input of sand and gravel can be ascribed to occasional ice rafting. The seabed sonar imagery data show that in Tunulliarfik reworking of the seabed due to iceberg ploughing was much more widespread than in Igaliku Fjord. The maximum water depth where iceberg plough marks were observed is about 80 m.

The core PO 243-443 from Igaliku Fjord (Fig. 5a) was collected at one of the rare sites where the sub-

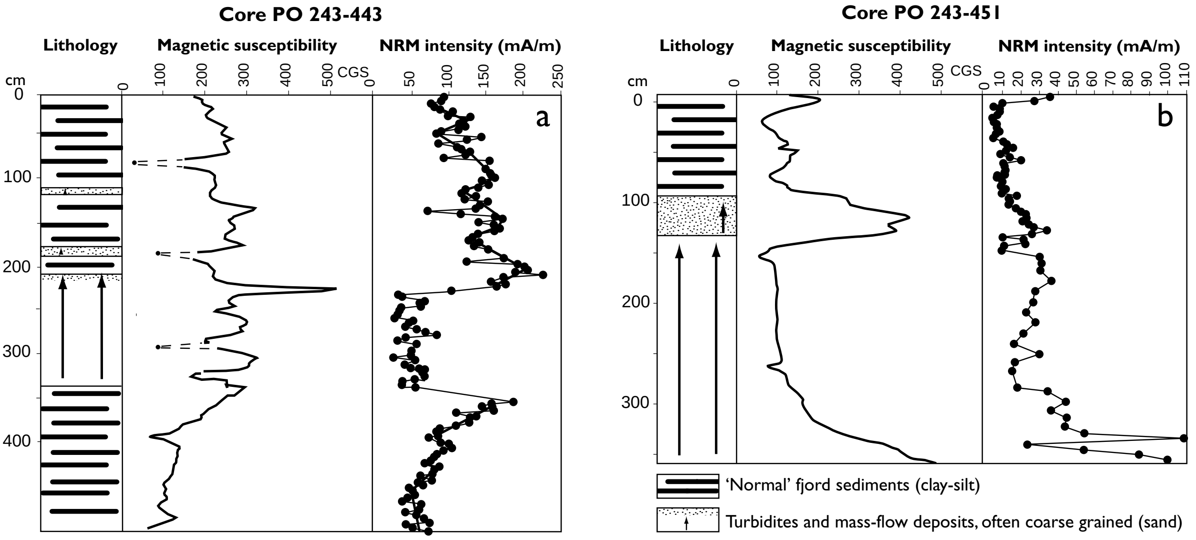

Fig. 5. Simplified lithological log with magnetic susceptibility profile (whole core measurements) and natural remanent magnetisation (NRM) intensity of **a**: core PO 243-443 and **b**: core PO 243-451. The magnetic properties generally reflect the lithological differences of the mass flow and turbidite units, when compared with the sediment intervals indicative of more quiet (normal) fjord sedimentation. Isolated magnetic susceptibility minima (see dashed line, core PO 243-443) presumably originate from measurement failure or disturbed sediment.

bottom profiler information indicated a sedimentary sequence not much affected by late Holocene sediment mass flow processes. The location of the site is shown in Fig. 3.

A box core (PO 243-430) was taken at the same site for which recent sedimentation rates were determined by ^{210}Pb and ^{137}Cs measurements. Results from these measurements indicate an average linear sedimentation rate of about 20 cm for the last 100 years. Both the lithological log of core PO 243-443 and that of core PO 243-451 (Fig. 5b) taken near Julianehåb show that relatively quiet sedimentary conditions prevailed during the time of deposition of the upper metre of silty clay and clayey silt. A preliminary estimate based on the ^{210}Pb information from core PO 243-443, suggests that the latter conditions may have been characteristic of the past *c.* 500 years.

Palaeomagnetic data show a declination record (not given here) with a westerly deflection, which in core PO 243-443 is confined within the 0.4–2.0 m interval. Such a westerly deflection is also found in core PO 243-451, where it is present within the upper metre of sediment. From historic and palaeomagnetic records from South Greenland and North-West Europe it is known that the declination was systematic to the west between AD 1600 and 1900. Within this context, it is interesting to refer to the magnetic susceptibility profile of core PO 243-443 (Fig. 5a), which displays markedly low values in the lowermost part of the core below 350 cm depth. In this part of the core sediments are, as in the upper metre, indicative of a normal, relatively quiet sedimentary environment, whereas the intermediate interval below about 110 cm, and more particularly below 175 cm subbottom depth, is characterised by the repeated occurrence of mass flow deposits which also includes coarser material. The natural remanent magnetisation (NRM) records shown in Fig. 5 clearly illustrate these differences in sediment type. The reason for significantly lower magnetic susceptibility values near the bottom of the core must be sought in sedimentary and physico-chemical conditions that were different from those prevailing in the period of sedimentation of the silty and clayey sediments of the top unit. Tentatively, it is concluded that climate conditions governing the fjord hydrography and the more regional (onshore) sedimentary processes must have been different, i.e. most likely characterised by higher temperatures than those of the Little Ice Age that followed.

Thus, although firmer conclusions must await the first results from the AMS ^{14}C measurements, we suggest that sedimentary conditions in the area have been relatively stable during the last 500 years or so. The same applies to the conditions prevailing during the Mediaeval Climatic Optimum. However, submarine sliding and slumping may have occurred frequently during the transition from one climate regime to the other, i.e. at the beginning of the Little Ice Age. Increased submarine slope instability during that time may be linked to the effect of generally intensifying atmospheric circulation, most likely resulting in more frequent storm surges with increased shallow water wave-action and sediment reworking. At shallow water depths seabed reworking by grounded ice may also have intensified. Enhanced niveo-fluvial sedimentary processes onshore may have additionally contributed to a larger sediment input to the fjords, thus further destabilising (overloading) the slope sediments. The latter processes may apply in particular to the study areas in the inner parts of the fjords.

However, more puzzling, and highly interesting with respect to the regional scale of the environmental changes observed, is the thick (> 2 m), extremely fine-grained and homogeneous turbidite unit found below 135 cm subbottom depth in core PO 243-451 (Fig. 5b). Although the base of the unit was not cored, the increased magnetic susceptibility values at the bottom of the core clearly indicate increasing grain sizes with depth, or a larger content of (titano-magnetite) heavy minerals, suggesting the presence of the base of the turbidite unit just below. The lithology of the deposit demonstrates an extremely distal setting. The core is located in a small trough in the central part of the fjord, with a direct connection to more open shelf waters not far away to the south-west. Therefore, we cannot exclude that fast turbidite sedimentation here could also have originated from an extreme sedimentation event triggered on the shelf. Further ongoing and planned analyses will certainly contribute to a better characterisation of the latter sedimentary processes.

In summary, it appears that various large-scale sediment disturbances have occurred both at the entrance and in the innermost part of Igaliku Fjord. Preliminary results from ^{210}Pb measurements and palaeomagnetic information suggest that these events were initiated at the beginning of the Little Ice Age. The results of AMS ^{14}C measurements currently being carried out at Aarhus University, Denmark will hopefully enable a more accurate timing of these sediment mass flow events to be determined in the course of the year.

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Limnological and palaeolimnological studies of lakes in south-western Greenland

N. John Anderson, Ole Bennike, Kirsten Christoffersen, Erik Jeppesen, Stiig Markager, Gifford Miller and *Ingemar Renberg*

The many lakes in south-western Greenland offer excellent opportunities for both limnological and palaeolimnological studies. The lack of any cultural disturbance means that these lakes are tightly and directly linked with their catchment areas and regional climate. As such, the development of the biological structure of these lakes over time should primarily reflect climate changes that have taken place since deglaciation. In turn, these changes in lake species composition and their productivity are preserved in the lake sediments. These lakes provide, therefore, excellent opportunities for studying the impact of past climatic changes on lake ecosystems. Similarly, the sediment records can also be used as proxies for palaeoclimatic changes. Clearly, however, to interpret sediment records in terms of fluctuating climate it is necessary to understand contemporary processes. The limnology of these lakes is not particularly well understood as only a few of the lakes have been studied, and then only infrequently, over the last 50 years (Williams 1991).

Field work in 1997 and 1998 between Kangerlussuaq and Kap Farvel (Fig. 1A), had three main aims:

1. To generate limnological data on the functioning of the lakes in a transect along Søndre Strømfjord. The 'saline' lakes in the Kangerlussuaq area, at the head of Søndre Strømfjord, have been known for some time (Böcher 1949; Williams 1991), although their origin is not completely understood and their limnology has not been studied in detail (Böcher 1949; Hansen 1970).

2. To collect sediment cores from the saline lakes in the Kangerlussuaq area and from lakes at the outer coast adjacent to the Labrador Sea (Fig. 1), where laminated lake sediments have been identified previously (Anderson & Bennike 1997; Overpeck *et al*. 1998).

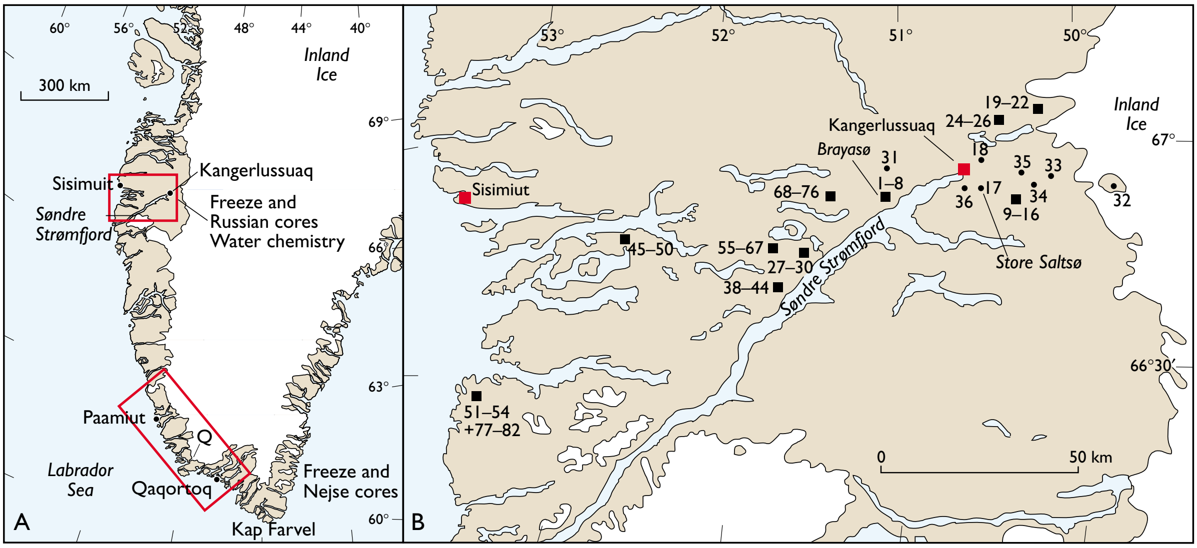

Fig. 1. **A**: The location of the study areas between Kangerlussuaq and Kap Farvel. Q: Nordre Qipisaqqu Bræ. **B**: The location of the limnological survey around Kangerlussuaq and north of Søndre Strømfjord, and the sites of specific lakes (e.g. 32) mentioned in the text (■ = group of lakes; • = individual lake).

3. To consolidate the surface sediment sampling programme started in 1996, particularly with a view to establishing a transfer function for lake-water conductivity for West Greenland (Anderson & Bennike 1997).

Laminated sediments in 'saline lakes' in the Kangerlussuaq area

During the course of taking surface sediment samples in 1996 a number of lakes with laminated surface sediments were identified. As it is very difficult to retain the laminated structure of surface sediments using normal gravity, piston or Russian corers due to the high water content, it is necessary to freeze the sediment *in situ* using a freeze corer. With this coring method, solid CO_2 mixed with ethanol is used to freeze sediment in a flat-sided metal container (Fig. 2A). As it is easier to take the full (Holocene) sediment sequence when working from the ice surface of a frozen lake, a number of lakes were re-visited in April 1997 to take freeze cores of the unconsolidated surface sediments and Russian cores (Fig. 2C) of the deeper sediments. We cored four lakes, three 'saline' lakes (Brayasø, lake 6 and Store Saltsø (Fig. 1; conductivities *c*. 3000 µS cm^{-1})) and a single fresh-water lake as a reference site (lake 2; conductivity 450 µS cm^{-1}). The sediment records of the three saline lakes are all clearly laminated throughout (Fig. 2B, C).

Laminations are formed by the preservation of distinct inputs to the sediment surface; annual laminations or varves result when there are distinct seasonal inputs each year. Such distinct seasonal inputs occur in most lakes as the result of annual peaks in phytoplankton productivity, meltwater inputs etc. Their preservation, however, requires more optimal conditions: reduced energy inputs to the lakes, deep water, and often an anoxic hypolimnion with low benthic invertebrate populations. Arctic lakes in general have extended periods of ice cover, around Kangerlussuaq the ice-free period is around three to four months. Ice cover reduces the amount of physical wind mixing of the water column and hence disturbance of the sediments. The long period of ice cover may account for the coarsely laminated structure observed in many West Greenland lake sediments. However, the very fine laminations (< 1 mm) preserved in Brayasø and lake 6, for example, require something more than extensive ice cover; this is probably the combination of meromixis and anoxia.

In closed-basin lakes, the concentration of salts in the lake water primarily reflects changing precipita-

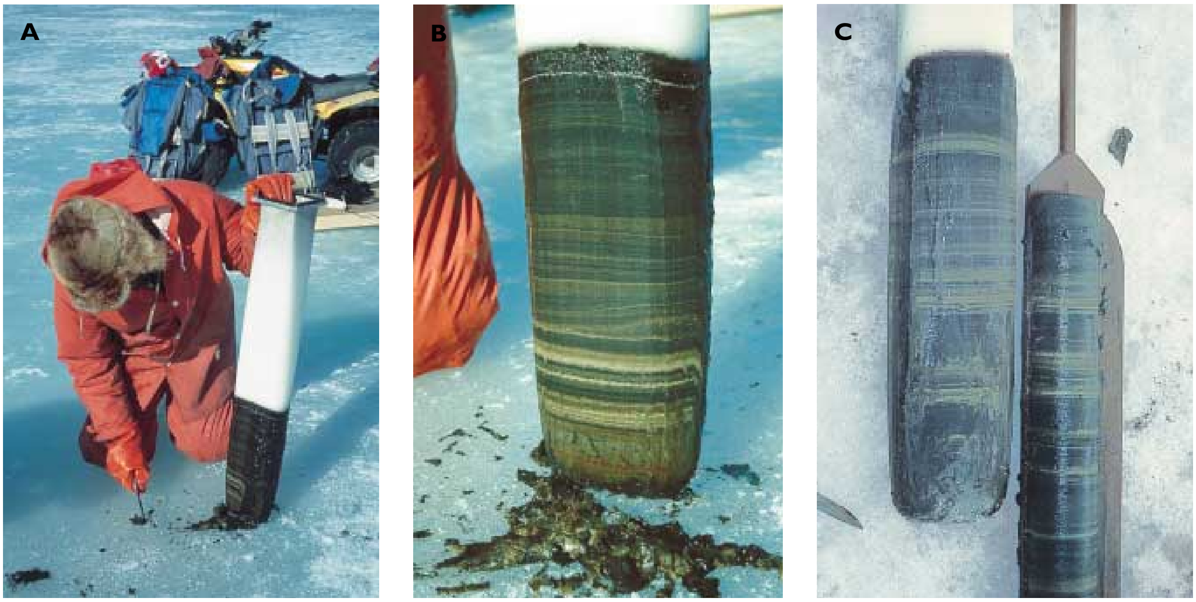

Fig. 2. **A**: The freeze corer immediately after retrieval showing the frozen sediment and the frozen overlying water. **B**: Close-up of a freeze core from Store Saltsø immediately after retrieval, showing the clear laminated structure of the sediment. **C**: Comparison of a freeze core of the surface sediments and Russian core (from Brayasø) demonstrating the ease with which the two core types can be correlated. The diameter of the Russian core, to the right, is 10 cm.

Fig. 3. **A**: Field camp near one of the lakes in April, 1998. **B**: The Nesje corer is lifted out of the sediment using a hi-lift jack.

tion/evaporation ratios and groundwater inputs. The latter are probably minimal in the Kangerlussuaq area due to the influence of permafrost. In this area, therefore, the record of changing lake water conductivity during the Holocene should reflect changes in local patterns of precipitation and evaporation, i.e. a record of regional climate change. As conductivity is a major influence on the diatom community composition of lakes, transfer functions are being developed using weighted averaging methodology. This transfer function will permit a quantitative reconstruction to be made of historical lake water conductivity and hence changing precipitation/evaporation ratios over time.

Coring in south-western Greenland adjacent to the Labrador Sea and implications for glaciation history

During March and April 1998, sediment cores were collected from two of the basins in southern Greenland where laminated sediments had previously been located, and two additional basins were cored. We camped at the lakes, and used a chartered Sikorsky S-61 to move the coring and camping equipment (Fig. 3).

Freeze cores were collected from the two basins with laminated sediments, one 25 km north-west of Qaqortoq (60°51.4´N, 46°27.8´W) and one 10 km north of Paamiut 62°5´N, 49°36.7´W) (Fig. 1A). From each lake six cores were taken, so that local differences from core to core could be eliminated. Both lake basins showed laminated sediments for the whole sampled interval, with a few turbidites present. The freeze cores were shipped frozen to Boulder, Colorado, USA where work is now in progress to establish whether the laminae represent annual layers (varves). The thickness of the laminae are being measured using a microscope, since the mean thickness of the laminations is only around 0.2 mm. From the same two lakes, and from two additional lakes, longer cores were collected using a Nesje corer (Nesje 1992). This is a percussion-piston coring system which can penetrate stiff sediments at water depths of up to *c.* 100 m. The corer is hammered down into the sediment using a weight with static ropes. Cores up to 4.5 m in length (8 cm diameter) were collected. Magnetic susceptibility was measured along each core using a Bartington loop prior to cutting the cores for shipping to Boulder.

Some radiocarbon dates based on humic acid extracts are now available from the Nesje cores. One is from an isolation basin near Paamiut, South-West Greenland (Fig. 1A) with a threshold at 17 m above sea level. A sample from the transition between the marine and lacustrine sediments yielded an age of 8.8 ka BP (uncalibrated radiocarbon years before present). This date is surprisingly old when compared with dates from other isolation basins in the area (Kelly & Funder 1974), but the sample may come from brackish water sediments rather than lacustrine sediments. At the coring site, at a water depth of more than 40 m, less than 90 cm of Holocene gyttja was recovered, which indicates a low sedimentation rate in this basin.

Another basin near Paamiut, and well above the marine limit, also contained less than 1 m of Holocene gyttja, the oldest part of which was dated to 9.6 ka BP. A lake basin 25 km north-west of Qaqortoq, contained *c.* 1.8 m of Holocene gyttja with a basal age of 9.1 ka BP, underlain by glacio-lacustrine sediment with clasts of gyttja. These clasts were dated to 9.6 ka BP, and the dates indicate deglaciation of the basin followed shortly afterwards by an early Holocene glacial re-advance and recession. The 9.6 ka BP date is the oldest date on Holocene sediments from this part of Greenland, and provides a minimum date for the deglaciation of this region.

The most impressive Nesje core sequence was obtained from a lake basin (61°0.7′N, 47°45′W) situated below the marine limit, close to Nordre Qipisaqqu Bræ, which is an outlet glacier from the Greenland Inland Ice (Fig. 1A). The thick sequence comprises glacio-marine sediments, marine sediments, lacustrine gyttja, clay gyttja, glacio-lacustrine sediments and 5 cm of gyttja. The lake was isolated from the sea around 8.4 ka BP, and the transition from gyttja to clay gyttja, which marks the onset of the neoglaciation, is dated to 4.0 ka BP. This, together with a similar date from eastern North Greenland (Bennike & Weidick 1999, this volume), is one of the best dates for the start of the neoglaciation in Greenland. The base of the glacio-lacustrine sediments is dated to 0.5 ka BP, which dates the beginning of the Little Ice Age.

Surface sediment sampling of lakes along a climatic gradient

The area from the margin of the Inland Ice at the head of Søndre Strømfjord westwards to the coast south of Sisimiut (Fig. 1B) represents a major climatic gradient, from more continental conditions close to the ice sheet to the more maritime influenced coastal zone. Mean summer air temperatures are higher at the head of the fjord, rainfall lower and there is greater evapotranspiration. Summers at the coast are generally cooler and damper with greater influence of local fog, with snowbanks remaining to late in the summer. It is a reasonable assumption that both lake community structure and productivity should reflect these climatic differences. Recently, attempts have been made to develop transfer functions that relate both diatoms and chironomids to climate variables, for example air or water temperature (e.g. Lotter *et al.* 1997). It is hoped to develop similar models for West Greenland. However, to develop similar models successfully requires a range of lakes covering the gradient to be modelled. Single measurements of lake-water temperature have limited usefulness. In 1998, thermistors to measure surface water temperature were put out in 20 lakes along a gradient from the Inland Ice margin to the coast (Fig. 1B). The thermistors were set to record lake water temperature every 30 minutes from 6 June until 10 September. The data obtained provide a reliable method of estimating mean surface water temperature, and are currently being related to data from the meteorological stations at Sisimiut and Kangerlussuaq.

The first lakes sampled in 1996 were limited to a lake (32) on a nunatak at the edge of the Inland Ice and other lakes up to *c.* 40 km to the west. The aim of the lake surface sediment sampling undertaken in 1997 and 1998 was, therefore, to complete the sampling of lakes along the climatic gradient between the Inland Ice margin and the outer coast. In 1997 a further 17 lakes were sampled in three separate groups: an intermediate group 60 km west of the airport at Kangerlussuaq, a group at around 400 m altitude, 40 km south-west of Sisimiut and a third group at the coast. The lakes in the last two groups had low conductivities (*c.* 40 µS cm^{-1}) whereas the first group included a lake (42; Fig. 1B) with higher than average conductivity (1600 µS cm^{-1}). Another 22 lakes were sampled in 1998, 30 km to the north-east of lake 42, and these included several lakes with higher than average conductivities. Such lakes (with conductivities of 1200 to 2000 µS cm^{-1}) are intermediate between the dilute outer coastal lakes and the area close to the

Fig. 4. Fossil shorelines at lake 70. The present-day conductivity of this lake is 2500 µS cm^{-1}.

airport at Kangerlussuaq, where the 'saline' lakes (Williams 1991) are found (conductivities around 3000 µS cm^{-1}). The latter probably only occur in those areas close to the head of the fjord with low precipitation/evaporation ratios. Lake 42 may represent an approximate outer (westerly) limit for the occurrence of the West Greenland type of saline lakes (Williams 1991). The palaeoclimatic significance of these lakes is indicated by the evidence of higher shorelines (Fig. 4). The implication is that the conductivity of the lakes has increased due to evaporation (see below).

Limnology of lakes in the Kangerlussuaq area

In 1996, the lake sediment sampling concentrated on obtaining surface sediment samples to be used for developing transfer functions for lake water conductivity and total phosphorus using diatom, zooplankton and chironomids remains in the surficial sediments (Anderson & Bennike 1997). Development of transfer functions requires some understanding of the contemporary lake communities and the way they function. Unfortunately, relatively little is known about the present day status of the lakes. Therefore, in an attempt to characterise the limnology of the lakes in the Kangerlussuaq area, a synoptic survey was started in 1997. The objectives were to collect physical, chemical and biological data for as many lakes as possible around Kangerlussuaq where sediment samples previously had been collected. In August 1997, a total of 19 lakes were sampled, including five saline lakes. The sampling programme included profiles of temperature, oxygen, pH, conductivity and light. Water samples for chemistry, phytoplankton, micro- and mesozooplankton were also collected at two depths (one if the water column was fully mixed). Samples of epiphytic algae were also collected and the macrovegetation was recorded and collected along a transect in each lake. In four lakes the light measurements were expanded to include measurements of spectral light attenuation and light absorption by particles.

As laminated sediments were found in a number of lakes it was important to know if the saline lakes were permanently stratified, as meromixis is a common cause of laminated sediments in both arctic and temperate lakes (Hardy *et al.* 1996). Figure 5 shows profiles of conductivity, temperature and oxygen for Brayasø, one of the five saline lakes sampled in 1997. Conductivity and temperature were uniform to a depth of 5.3 m where there was a sharp pycnocline where the conductivity increased by 30% (> 600 µS cm^{-1}) in just over 0.2 m water depth (Fig. 5). Below the pycnocline there was a gradual decline in temperature, reflecting the attenuation of light with depth, and thereby decline in the accumulation of solar energy. An interesting aspect was that the difference in salinity between the less saline surface layer and the dense hypolimnion was large enough to maintain a stratification when the surface layer cools in the autumn. The lake is, therefore, permanently stratified and must be classified as a meromictic lake.

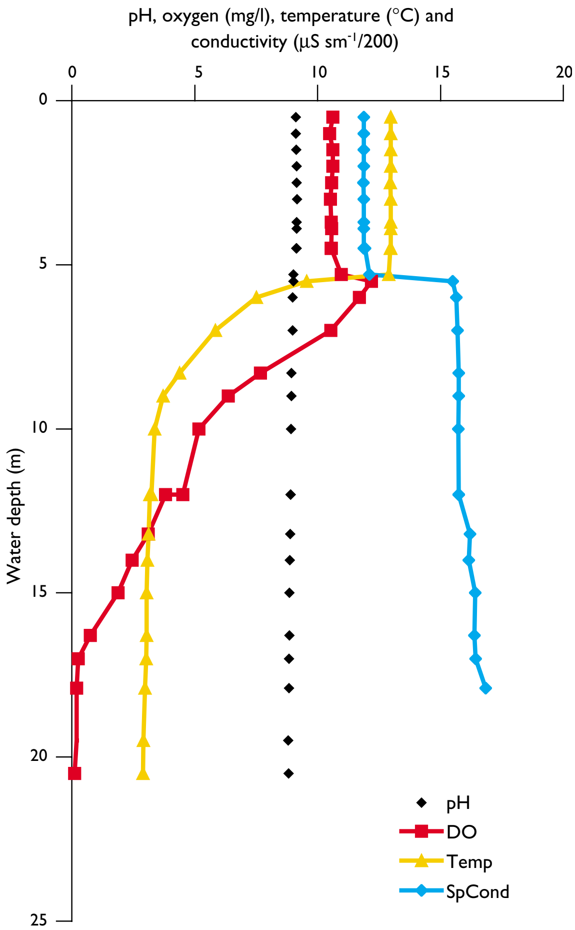

Fig. 5. Profiles of dissolved oxygen (DO), conductivity (µS cm^{-1}; spCond), pH and temperature (temp °C) for Brayasø in August 1997 plotted against depth in the lake.

To our knowledge this is the first time that a meromictic lake type has been recorded in the Arctic for a lake not formed due to isostatic uplift of a fjord (e.g. Quellet *et al.* 1989; Overpeck *et al.* 1998). Brayasø is located about 200 m above sea level. There is no outflow from the lake and the salinity must come from salts that are washed out of the soil (atmospheric inputs are low) and accumulate in the lake over time. This means that the salinity in the lake and the associated meromixis are of arid origin, whereas most other saline lakes in the Arctic are saline because of their proximity to the sea (e.g. Quellet *et al.* 1989; Ludlam 1996; Overpeck *et al.* 1998). Similar profiles of conductivity and temperature were measured in the other four saline lakes, while the 14 freshwater lakes had a normal circulation pattern. Most of the latter are dimictic with a period of summer stratification, where the surface temperature reaches *c.* 13°C.

Another aspect of the limnological survey was the relationship between circulation pattern within a lake, its macrovegetation and the oxygen concentrations in the hypolimnion. Figure 5 shows that the oxygen concentration was uniform in the well-mixed epilimnion, while an oxygen maximum occurred at the pycnocline due to an accumulation of phytoplankton at this depth. Below the pycnocline there was a gradual decline in oxygen with depth, with anoxic conditions at the bottom. This profile (Fig. 5) is in contrast to the other saline lakes where oxygen is found all the way to the bottom. The reason for this difference is that macrovegetation was absent in Brayasø below 4 m, whereas the other saline lakes had macrovegetation below the pycnocline, which prevented oxygen depletion in the hypolimnion.

Finally, by sampling 19 different lakes we aimed to characterise the biological structure of the plankton community and the macrovegetation, in particular mosses which form dense mats in many lakes. The lakes covered a broad range of salinity and dissolved organic carbon concentrations, and some support fish populations (stickleback and Arctic char). The sampling programme included measurements of the standing stock of bacteria, protozoa, phytoplankton, rotifers and zooplankton in the water column. The samples are still being processed, but it is already clear that the lakes show distinct biological differences, especially regarding the phytoplankton and zooplankton abundance and biomass. The substantial differences in biological structure among the lakes probably reflects the influence of both the fish populations (on the lower trophic levels) and the ionic content of the water. The limnological survey was continued in 1998 at the two coastal lake groups. The investigation was similar to that carried out at the head of the fjord (above), but with the inclusion of gill netting to determine the abundance and size structure of fish.

It is expected to be able to describe in reasonable detail the biological structure of the lake types found along the gradient from the Inland Ice to the coast. This will provide the opportunity to relate the occurrence of microfossils (diatoms, zooplankton, chironomids) in the surface sediment to the biological and physical structure, particularly salinity and nutrients of the lakes, and allow an evaluation of past and present climate and trophic changes.

Conclusions

High temporal resolution records of climate proxies (such as lake water conductivity) are very important for determining time scales of former climatic variability. The best temporal resolution obtainable from lake sediments is from varves, where inter-annual resolution can be combined with an absolute chronology (by counting the number of varves). This combination of laminated sediments and the possibility of the application of a quantitative climate proxy (diatom-inferred conductivity) is very promising. Although it is not yet known whether the laminated sediments from the south-western Greenland lakes are varves, the detailed and variable structure of laminations at Store Saltsø, Brayasø and other lakes (Fig. 2B, C) should contain climatic and environmental information. To extract this information it is important to understand both the ecological and physical limnological processes that result in these laminations and how they reflect local climate and catchment processes. In addition, the sediment records from lakes in Greenland also hold a large potential for studies of glaciation history and sea-level changes.

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Airborne geophysical maps

Disko Bugt – Nuusuaq region, central West Greenland (Aeromag 1997)

Maps of magnetic field intensity and associated vertical derivative, flight path and digital elevation model derived from radar measurements. Maps in scale 1:50 000, 1:250 000 and 1:500 000. Aeromagnetic survey flown *by* Sander Geophysics Ltd., Ottawa, Canada.

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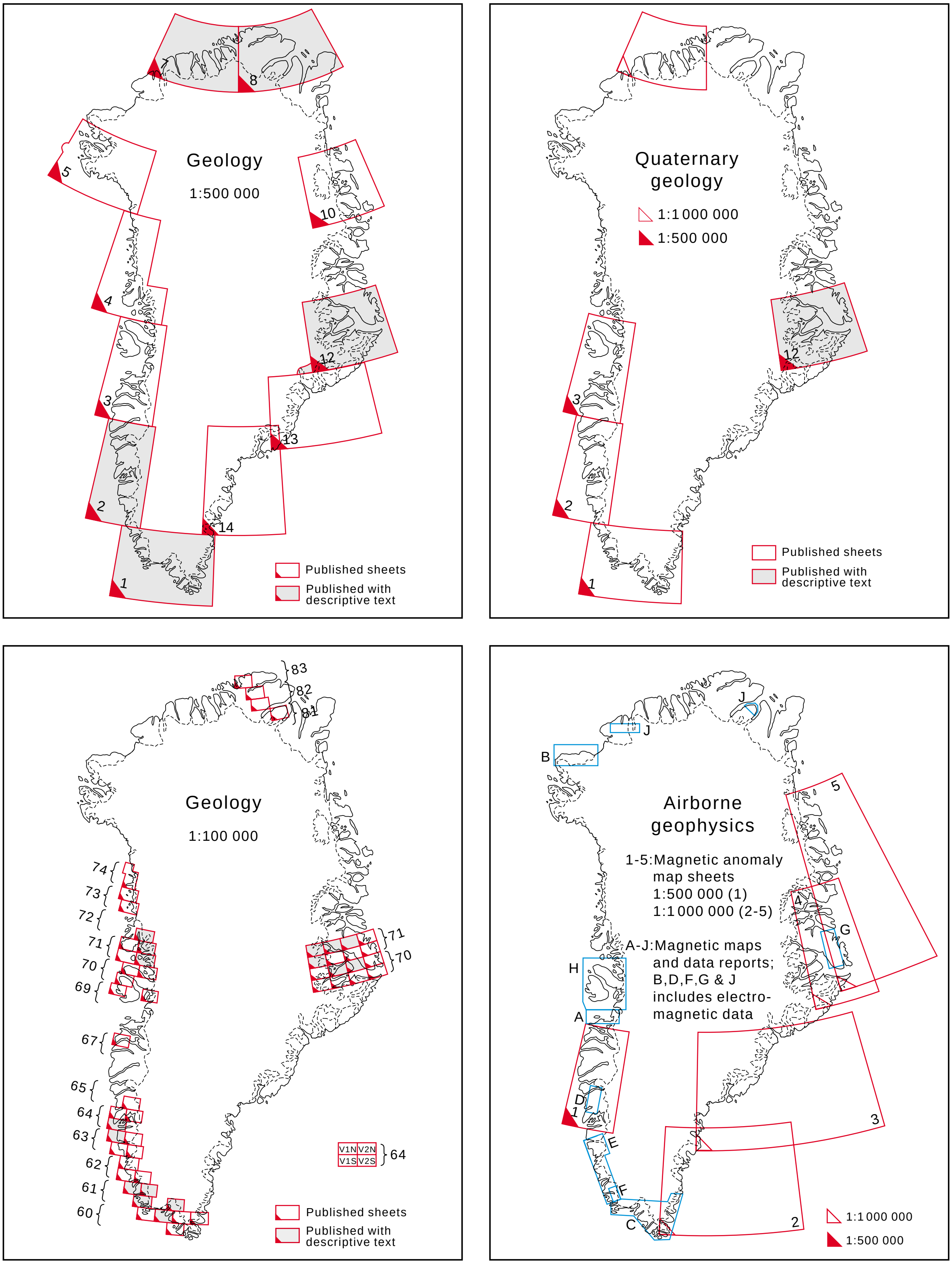

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1998/5 Reservoir modelling of western Nuussuaq, central West Greenland. EFT-96 project 1313/96-0010 final report. 3 vols., 14 appendices. *By* G. Dam, M. Sønderholm, T. Kierkegaard, L. Kristensen, H. Nøhr-Hansen, J.A. Chalmers, C. Marcussen, J.A. Bojesen-Koefoed, F.G. Christiansen, Å. Nielsen, P.R. Andersen & G. Andersen.

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Issue No. 14, March 1998, 13 pp.
Leading article: The Canada–Greenland geological link in focus again, new carbonate-hosted Zn-Pb-Ag occurrence.

Issue No. 15, November 1998, 8 pp.
Leading article: Bureau of Minerals and Petroleum (BMP). New Greenland governmental office.

Ghexis Newsletter

Issue No. 13, May 1998, 6 pp.
Leading article: Mineral Resources Administration to be transferred to the Greenland Home Rule Government from July 1, 1998.

Issue No. 14, December 1998, 8 pp.
Leading article: New exploration opportunities – West Greenland.

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The list contains three types of article: (1) from peer review international journals, (2) from proceedings volumes, and (3) from unedited reports. Articles written by non-survey staff, where the basic work was initiated under the Survey's auspices, are also included, as well as those attached to the Danish Lithosphere Centre (DLC).

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Range and 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 the colophon page of this volume. Of the publications listed here some can be sent free of charge, for example the newsletters to the international mining and oil industries, viz. *Greenland MINEX News* and *Ghexis Newsletter*, respectively, as well as the *Catalogue of Greenland publications and data*, see under 'Publications catalogue and reports' (p. 78).

The *Catalogue of Greenland publications and data* contains a complete list of the geoscientific publications issued by the Survey (bulletins, reports, maps, etc.) going back to the first bulletin released in 1948. It also contains a data directory specifying the range of data and services available from the Survey including: data base facilities; map, sample and drill-core archives; bathymetric and topographic maps; satellite data; as well as bibliographic and library facilities including unpublished maps and reports from the Survey's own activities and those of industry.

Information about the present range of publications from the Geological Survey of Denmark and Greenland, both printed and electronic issues, can be found on the Survey's web-site www.geus.dk

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