GEOLOGY OF GREENLAND SURVEY BULLETIN 180 • 1998

Review of Greenland activities 1997

GEUS

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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Greenland activities 1997, mineral resource studies, petroleum geology, airborne geophysics, geological mapping, climatic research, publications review.

Cover
Ella Ø, North-East Greenland, where sedimentological studies of the Eleonore Bay Supergroup were carried out as part of a regional mapping programme. Snow-covered mountains in background are in eastern Suess Land, with summits reaching 1874 m. Photo: Jakob Lautrup.

Frontispiece: facing page
In 1997 a two-year programme of regional geological mapping was begun in North-East Greenland between latitudes 72° and 75°N. Field teams were supported from a main base at Mestersvig (72°N) and a satellite tent base in Grejsdalen, Andrée Land (73°30′N). Photograph shows a view eastwards along Grejsdalen. Mountains in left background are formed by flat-lying sediments of the Neoproterozoic Eleonore Bay Supergroup, which are invaded by Caledonian granites (light rocks to the left of the prominent moraine). Summits reach 2000 m, about 1500 m above the valley floor. Photo: Jakob Lautrup.

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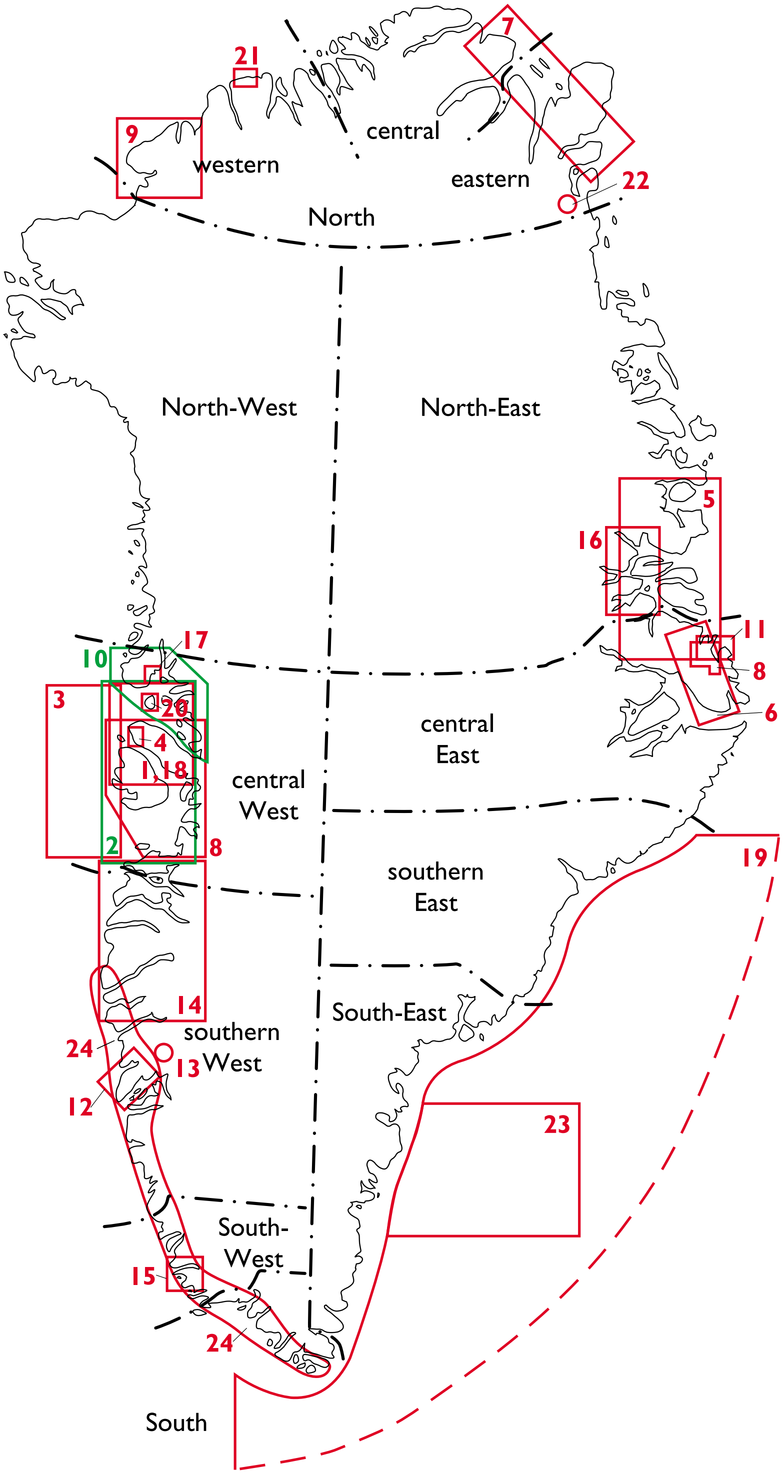


Locality map for contributions in this Review of Greenland activities. Numbers locate the individual papers in the table of contents opposite, although papers dealing with the whole of Greenland are not located.

Contents

Bold numbers refer to the location map opposite

A review of Greenland activities, 1997

Martin Ghisler
Director

Field activities undertaken by the Geological Survey of Denmark and Greenland (GEUS) in and around Greenland were at an relatively high level in 1997. A total of 115 scientific and technical personnel took part in GEUS expeditions, including 13 from the Danish Lithosphere Centre. The Survey's total full-time staff numbers 360, of which 95 are concerned with projects in relation to Greenland. In addition the 20 staff of the Danish Lithosphere Centre, a research centre funded by the Danish National Research Foundation and administratively linked to GEUS, are mainly involved in research activities centred on Greenland.

The Greenland Home Rule Government has a representative on the Survey's Board of Management, and thus has direct influence on setting priorities for the institution's varied projects. The Greenland Government Minerals Office (from January 1998, the Bureau of Minerals and Petroleum) has also directly financed joint projects with GEUS, in particular airborne geophysical surveys, with a budget in 1997 of 18 million kroner. This supplements the grant of 35 million kroner provided by the Finance Law for Denmark dedicated to Greenland projects. Together with other sources of income, the total Survey budget expended on Greenland activities in 1997 amounted to 70 million kroner.

As part of the agreement dated 14 November 1994 between the Prime Minister of Denmark and the Premier of the Greenland Home Rule Government, concerning strengthening of the mineral resources sector in Greenland, two GEUS geologists were seconded to the Greenland Government Minerals Office in Nuuk throughout 1997. This arrangement covers both the oil resources and mineral resources sectors, and involves two-way communication of geological information of particular relevance to the non-living resource sector.

GEUS, in cooperation with the Mineral Resources Administration for Greenland, Danish Ministry of Environment and Energy, and the Minerals Office in Nuuk, has continued the joint information service directed at the international oil and mining industries. This activity concentrates on the presentation of geological results and information relevant to resource prospecting on land and offshore at meetings, symposia and exhibitions, in addition to the distribution of publications, newsletters and reports. In the field of mineral resources, particular efforts have been directed at Canadian companies, and in respect of oil resources to companies in both North America and Europe.

GEUS has assisted the Mineral Resources Administration for Greenland in geological questions concerning the activities of companies with concessions in Greenland, including monitoring of grønArctic's activities on Nuussuaq, the work of the Statoil group on the Fylla Banke, and with respect to new mineral concessions in West Greenland the area calculation of mineral licences. In the summer of 1997 GEUS monitored Rio Tinto's drilling activity on iron ore deposits east of Nuuk on behalf of the Mineral Resources Administration for Greenland (Fig. 1, **A**).

The Danish National Research Foundation has announced that funding for the Danish Lithosphere Centre is to be extended for a further five-year period (1999–2004) with a grant of 85 million kroner.

Geological mapping

Systematic geological mapping for the 1:500 000 map series has been continued, and in 1997 as the Survey's largest single activity a two-year project with significant international participation was initiated in North-East Greenland (72°–75°N: sheet 11, Kong Oscar Fjord; Fig. 1, **3**). Field work in 1997 was concentrated in the southern part of the map sheet, with investigations of the composition, structure and age of the lithological units making up the Caledonian fold belt, and studies of the post-Caledonian strata to the east. During the summer the expedition was visited by the Danish Minister

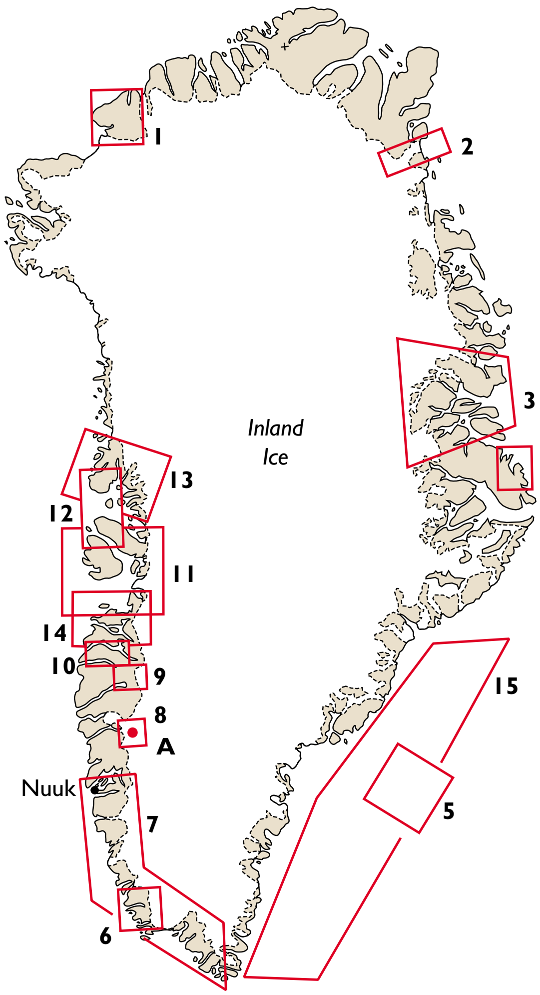


Fig. 1. Survey activities in Greenland in 1997. **A**: Commercial drilling activity, north-east of Nuuk; **1**: Ore geological studies, Washington Land; **2**: Nioghalvfjerdsfjorden glaciological studies; **3**: Regional geological mapping, North-East Greenland; **4**: Geophysical survey south of Mestersvig; **5**: Marine geological survey offshore South-East Greenland; **6**: Plate tectonic studies north of Ivittuut; **7**: Lake sediment investigations, West Greenland; **8**: Ancient life studies, Isua; **9**: Lake sediment studies, Kangerlussuaq; **10**: Hydrological and glaciological reconnaissance, north-east of Sisimiut; **11**: Aeromagnetic survey, West Greenland; **12**: Hydrocarbon studies, Nuussuaq Basin; **13**: Ore geochemical studies, West Greenland; **14**: Danish Lithosphere Centre, geological studies, West Greenland; **15**: Danish Lithosphere Centre seismic survey, offshore South-East Greenland.

for Research, Jytte Hilden, and the Greenland Home Rule Government Minister for Research, Marianne Jensen.

East of Nuuk in West Greenland, a major research project coordinated by GEUS, focused on the search for traces of life in some of the oldest known rocks on Earth in the Isua area (Fig. 1, **8**). In addition to detailed geological mapping a series of specialised studies will be undertaken by a group of scientists from the United Kingdom, France, Germany, USA and Australia.

In the northern border zone of the Ketilidian orogen north-east of Ivittuut (Fig. 1, **6**) in South-West Greenland, studies undertaken in cooperation with a British geologist are aimed at elucidation of plate tectonic processes 1800 Ma years ago.

A programme to digitalise the Survey's 1:500 000 geological map sheets, undertaken in cooperation with the Minerals Office in Nuuk, has been completed; CD-ROM products will be released in 1998.

Work by the Danish Lithosphere Centre in 1997 was limited to onshore studies in the region between Sisimiut and Aasiaat (Fig. 1, **14**), and a seismic survey offshore South-East Greenland (Fig. 1, **15**).

Mineral resource investigations

As part of the continuing emphasis on promotion for the exploration of Greenland's natural resources, airborne geophysical surveys were flown in 1997 over areas in both East and West Greenland. The surveys were managed by GEUS, and carried out by international geophysical contractors; they were financed by special grants from the Greenland Home Rule Government. A magnetic survey was flown over the land and sea areas between Aasiaat and Uummannaq (Fig. 1, **11**) in West Greenland, and a magnetic and electromagnetic survey was flown over a particularly prospective area south of Mestersvig (Fig. 1, **4**) in East Greenland. The data acquired are included in geoscientific databases at the Survey, where they can be consulted by industry.

As part of the regional 1:500 000 geological mapping project in North-East Greenland (Fig. 1, **3**), geological and geochemical investigations were carried out with particular interest in possible gold mineralisation.

As part of the Polar Research Programme of the Danish Natural Science Research Council, ore geological investigations were carried out in Washington Land (Fig. 1, **1**), western North Greenland, and revealed hitherto unknown indications of zinc, lead and silver mineralisation.

In the Uummannaq and Upernavik kommunes (Fig. 1, **13**) in cooperation with the Minerals Office in Nuuk, ore geological investigations were carried out, partly using Greenland-trained prospectors. Systematic sand sampling was undertaken from rivers in the region which, after treatment and chemical analysis, will provide the mining industry with the possibility of evaluating the presence of possible mineral resources.

Petroleum geology

In the Nuussuaq–Svartenhuk area (Fig. 1, **12**) field investigations were carried out with the objective of evaluating the hydrocarbon prospects of the Nuussuaq Basin and the adjacent offshore region. Both the sedimentary and volcanic sequences in the region have been investigated, and led to finds of widespread oil seeps. Rock cores from drilling by the Survey and the commercial company grønArctic Energy Inc. have been the subject of detailed laboratory analysis. The GEUS investigations were supported by special grants from the Danish State and the Greenland Home Rule Government (until end 1997), from the Danish National Energy Research Programme, from the Greenland Home Rule Government, and from the Carlsberg Foundation. The results of the GEUS investigations are of fundamental importance in strengthening the interest of the international oil industry in West Greenland.

The Survey's regional mapping project in North-East Greenland (Fig. 1, **3**) included, as part of the Danish Natural Science Research Council's Polar Research Programme, petroleum geological investigations of the post-Caledonian sedimentary basins. Within the scope of the same programme, studies were undertaken in Washington Land (Fig. 1, **1**) of the source and reservoir properties of selected sedimentary rocks and bitumen residues.

Climate research and marine geology

The floating glacier which fills the interior of Nioghalvfjerdsfjorden in North-East Greenland (Fig. 1, **2**) was again the focus of international glaciological investigations. Studies of mass balance, glacier movement and melting on the underside of the glacier in contact with sea water were carried out. Among other results, melting at the underside of the glacier was found to be considerably greater than previous estimates.

Investigations of lake sediments and their microfossil and pollen contents around Kangerlussuaq in West Greenland (Fig. 1, **9**) have provided data on environmental and climatic developments since the last ice age. Studies of variation in lake sediments along the West Greenland coast (Fig. 1, **7**) have also provided information on climatic changes.

Marine geological surveys offshore South-East Greenland (Fig. 1, **5**), including seismic surveys and recovery of shallow seabed cores, were carried out as part of a project to map former ocean current systems between Greenland and Iceland. In the same general region (Fig. 1, **15**) the Danish Lithosphere Centre completed a seismic survey in preparation for planned drilling in 1998.

North-east of Sisimiut (Fig. 1,**10**) in West Greenland, GEUS in cooperation with ASIAQ (Greenland Field Investigations) carried out hydrological and glaciological reconnaissance. Field work is aimed at the modelling of drainage basins and contributes to general models designed to evaluate future utilisation of Greenland's water resources.

The climatic research activities of the Survey are an integral part of international climate research carried out in close cooperation with institutes in Canada, Germany, Norway, Russia, Sweden, Switzerland, The Netherlands and USA.

Publications

In 1997 GEUS published five numbers in the new Bulletin series, *Geology of Greenland Survey Bulletin* (nos 173, 174, 176, 177, 178). Number 176, *Review of Greenland activities 1996*, provided an overview of the year's activities in 18 articles (see p. 172, this volume). One sheet in the Geological map of Greenland 1:500 000 series was issued (sheet 10, Dove Bugt), together with two sets of geophysical maps from respectively South-West Greenland (Aeromag 1996) and an area around Ivittuut (AEM Greenland 96). In the Survey's open file type series *Danmarks og Grønlands Geologiske Undersøgelse Rapport*, 26 geological reports were issued which have relevance to Greenland. Three issues of *Greenland MINEX News* (nos 11, 12, 13) and two issues of *GHEXIS* (nos 11, 12), the Survey's international newsletters to respectively the mining and oil industries, were released in 1997.

Petroleum geological activities onshore West Greenland in 1997

Flemming G. Christiansen, Anders Boesen, Jørgen A. Bojesen-Koefoed, Finn Dalhoff, Gregers Dam, Philip S. Neuhoff, Asger K. Pedersen, Gunver K. Pedersen, Lotte S. Stannius and Kim Zinck-Jørgensen

The 1997 summer season saw continued petroleum geological activities in the Disko–Nuussuaq–Svartenhuk Halvø area, onshore West Greenland. These activities mainly took the form of a geological field project led by the Geological Survey of Denmark and Greenland (GEUS), whereas the continued exploration by grønArctic Energy Inc. (grønArctic) in the third year of their licence was kept at a very low level without field work, geophysical surveys or drilling. Furthermore an airborne geophysical survey, Aeromag 1997, covering a large part of the Disko Bugt area, was carried out in the early summer of 1997 with GEUS as project manager (Stemp 1997; Stemp & Thorning 1998, this volume).

Field work

The aim of the field work in 1997 was mainly to follow-up previous studies on Disko and Nuussuaq. In particular, this involved further search for, and sampling of, seepage and oil staining, not only on Disko and Nuussuaq, but also farther to the north on Ubekendt Ejland and Svartenhuk Halvø (Fig. 1). Sedimentological studies concentrating on general depositional models of the Upper Cretaceous and Paleocene successions were carried out on Disko and Nuussuaq. The structural studies of the western part of Nuussuaq were continued and a new study of the regional zeolite zonation of the volcanic succession on Disko and western Nuussuaq was initiated.

Seep studies

Encouraged by the many new oil seeps discovered during the 1996 field work and the subsequent organic geochemical results that have demonstrated at least five distinct oil types (Christiansen *et al.* 1997; Bojesen-Koefoed *et al.* in press), 'oil hunting' continued in 1997. Localities were selected on the basis of combinations of volcanic stratigraphy, structural position, lithology, porosity, and secondary structures in the volcanic rocks (Christiansen *et al.* 1997; Bojesen-Koefoed *et al.* in press); combining visual characteristics with the presence of a petroliferous odour was used successfully to locate new seeps on Nuussuaq as well as in areas farther to the north.

Many new localities were found and sampled in the vicinity of previously recorded seeps, especially in the area between the well sites GRO#3, GANE#1 and Sikillingi (Fig. 1). Much denser sampling was carried out in order to map the distribution of different oil types, and particularly in order to study the importance of the mixing of different oil types during migration, trapping and leakage. In two areas in particular, viz. Marraat and Sikillingi, major reservoir-like accumulations of almost non-degraded oil occur at or near to the surface plugging all available porosity in the volcanic rocks. Conservative calculations (see details in Bojesen-Koefoed *et al.* in press) suggest in-place oil volumes of several hundred millions of barrels and thereby indicate that the source rock(s) must have had a considerable generative potential, possibly sufficient to fill giant structures elsewhere or deeper in the basin.

New seep localities were also found in the north-western part of Disko and also in several places on Hareøen (Fig. 1). It is remarkable that pervasive oil staining has been recorded for the first time from outcropping sediments in West Greenland. Oil stained sediments have previously only been described from the cores of GANE#1 and GANK#1 (Christiansen *et al.* 1996) while one example of strongly altered bitumen on a sandstone surface was noted on Qeqertarssuaq by Henderson (1969). The documentation of relatively pervasive oil staining (moderately biodegraded) at Asuk on northern Disko (Fig. 3) looks promising for more discoveries in the future and for predicting a widely distributed oil-prone source rock in the non-marine Atane Formation of Cretaceous age.

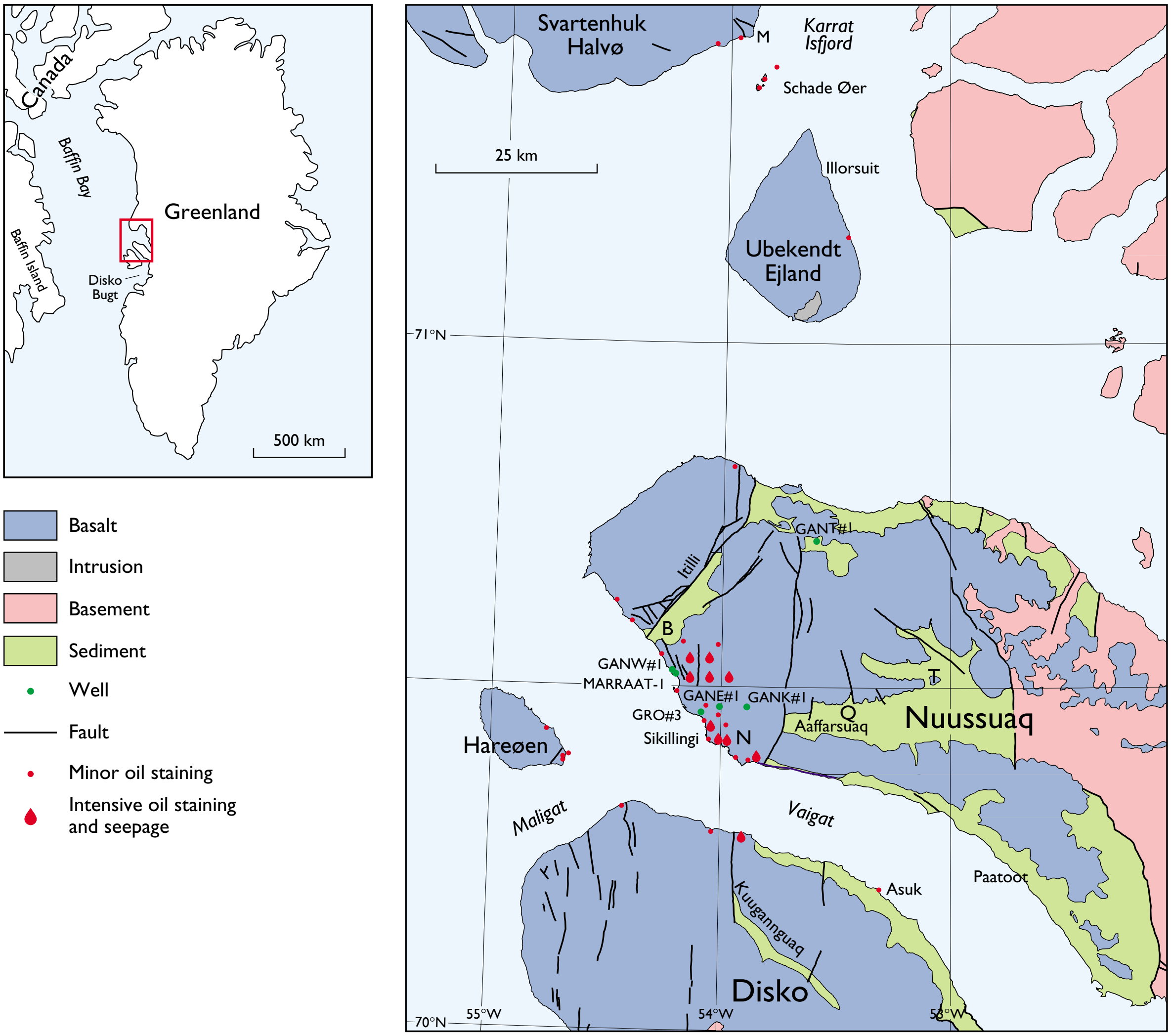


Fig. 1. Simplified geological map of the Disko–Nuussuaq–Svartenhuk Halvø area showing the position of wells and boreholes, and distribution of localities with seepage and staining of oil found in the period 1992–97. B: Bartschiakløft, M: Maniiseqqut, N: Nuusap Sanningasua, Q: Qilakitsoq, T: Tunoqqu. Based on published Survey maps.

Systematic search for oil staining was carried out for the first time within the Tertiary volcanic rocks to the north of Nuussuaq and led to several significant finds documenting the presence of oil over a distance of more than 150 km from Disko to Svartenhuk Halvø. The south-east coast of Ubekendt Ejland proved to be barren, probably due to metamorphism caused by heating from intrusions, but a systematic investigation along the east coast of the island led to location of a significant oil staining at a dyke contact about 12 km to the south of Illorsuit (Fig. 2), whereas most of the other tested localities were barren. On the small islands and skerries of Qeqertat (Schade Øer) in Karrat Isfjord weak but significant oil staining was found in hyaloclastite and lava belonging to the lower part of the volcanic succession. Further to the north around Maniiseqqut on the south coast of Svartenhuk Halvø a zone of intense oil impregnation was found within hyaloclastite cut by a major dyke. These rocks form the lowermost volcanic lithologies on Svartenhuk Halvø. A systematic search of the south coast of Svartenhuk Halvø over a distance of 35 km towards the west revealed only two localities with weak oil stains, both in carbonate veins along dykes cutting the lower part of the volcanic succession.

Fig. 2. Prominent N–S trending (190°/65° E) dyke from the eastern part of Ubekendt Ejland. Oil impregnation is common at the contact between volcanic rocks and the dyke. Person for scale.

Sedimentological investigations

A recently completed reservoir study of the most prospective area on Nuussuaq concludes that potential reservoir units include fluvio-deltaic sandstones of the Cretaceous Atane Formation, mid-Cretaceous–Paleocene marine slope channel sandstones and marine canyon sandstones equivalent to the incised valley fill sandstones of the Paleocene Quikavsak Member (Sønderholm & Dam 1998).

During the 1997 field season a number of outcrop studies were carried out in order to follow-up on the reservoir study and on previous year's field work on these stratigraphic units. The Atane Formation was studied on southern and central Nuussuaq, the Cretaceous–Paleocene slope succession was studied in the Aaffarsuaq valley, central Nuussuaq and the Paleocene unconformity and the incised valley sandstones were studied on northern Disko and on the south coast of Nuussuaq.

The Atane Formation is interpreted as an Upper Cretaceous succession of deltaic deposits characterised by accumulation of organic matter in non-marine environments. A major part of the 1997 field work aimed at a lateral correlation of measured sections. Lateral facies variations were noted in many of the depositional units suggesting that potential reservoirs are heterogeneous. The field work will be continued with the purpose of interpreting sediment transport directions, facies architecture and changes in delta palaeogeography, and establishing a depositional model for the Atane Formation. A depositional model may form the basis for the prediction of good reservoirs within the Atane Formation. The importance of the Atane Formation as a potential reservoir unit is stressed following the 1997 discovery of oil impregnation at Asuk.

The marine slope channel sandstones were studied in a possible Campanian succession exposed on the northern slopes of Aaffarsuaq between Qilakitsoq and Tunoqqu. A major unconformity separates the slope deposits from the deltaic deposits of the underlying Atane Formation. The boundary with the overlying ?Maastrichtian–Paleocene sediments is less distinct because the nature of the ?Campanian sediments is very similar to the sediments above and interpretation of the exact position of the boundary must await a detailed palynostratigraphic analysis. The ?Campanian marine

Fig. 3. Mid-Cretaceous sandstones of the Atane Formation unconformably overlain by Paleocene marine mudstones. A thin conglomerate separates the sandstones from the mudstones above. A normal fault showing a downward vertical displacement of the Paleocene mudstones by *c.* 20 m occurs in the right side of the picture. The yellow colour of the sandstones is due to oil staining. From Asuk at the north coast of Disko.

Fig. 4. Incised valley sandstones of the Paleocene Quikavsak Member. The valley is 190 m deep and *c.* 2 km wide and cuts into mid-Cretaceous fluvio-deltaic deposits of the Atane Formation. The valley sandstone is succeeded by offshore marine mudstones. Paatoot at the south coast of Nuussuaq.

slope sediments consist of mudstone, thinly interbedded sandstone and mudstone, and coarse-grained slope channel sandstones (deposited from high and low density turbidite currents), and sandy debris flows and slumps. The lower unconformity and the general chaotic nature of the sediments suggest syn-tectonic deposition during a previously unknown tectonic event in the Campanian. The ?Campanian slope sandstones constitute potential reservoir units, but the predictability is low due to the chaotic nature of the sediments.

During the Late Maastrichtian the area became tectonically unstable and was subjected to block faulting. Several phases of uplift, valley and canyon incision and infilling occurred, continuing into the Paleocene. This tectonic phase has been related to the earliest influence in the area of the Iceland mantle plume at the base of the lithosphere (Dam *et al.* 1998). The Paleocene unconformity was studied at Asuk on the north coast of Disko and at Paatoot on the south coast of Nuussuaq. In the Asuk area, the unconformity is succeeded by a conglomerate or by a thin sheet of shoreface deposits separating the mid-Cretaceous Atane Formation from unnamed Paleocene mudstones above. At this locality oil staining was found in the uppermost 3 m of the sandstone below the unconformity and the mudstones seem to form the main seal (Fig. 3).

At the south coast of Nuussuaq the unconformity is marked by a major valley incision (Fig. 4; Dam & Sønderholm 1998). The seaward extensions of these valleys into deeply incised marine canyons are regarded

Fig. 5. Young generation of N–S trending mineralised fractures cutting through clasts in the hyaloclastites. From the Sikillingi area, Nuussuaq. Pencil for scale.

as one of the best potential reservoir units in western Nuussuaq (Kristensen & Dam 1997; Sønderholm & Dam 1998). A number of detailed sections were measured across the unconformity and a series of small-frame colour photographs were taken from a helicopter with 60% overlap to provide stereoscopic models that are usable for multimodel photogrammetrical analysis. Within the incised valley fill a possible lacustrine source was sampled. Preliminary analyses show TOC values between 7% and 11%, and HI values up to 175.

Studies of Tertiary basalts

The oldest Tertiary volcanic rocks in West Greenland have been shown to host a major part of the discovered oil seeps and impregnations. In order to study the relationships between volcanism and the development of sedimentary basins, and in particular to study the progression of the volcanic rocks at the time of the initiation of volcanism, the oldest lavas, volcanogenic conglomerates and hyaloclastites on Nuussuaq and Hareøen were sampled for chemical and lithological analysis. In addition the lateral lithological variations were documented through systematic stereo-photography in order to provide material for multi-model photogrammetrical analysis. This investigation is expected to enable a three-dimensional reconstruction of the early volcanic basins to be made which will also include the thick volcanic successions encountered in drill cores on western Nuussuaq.

Structural studies

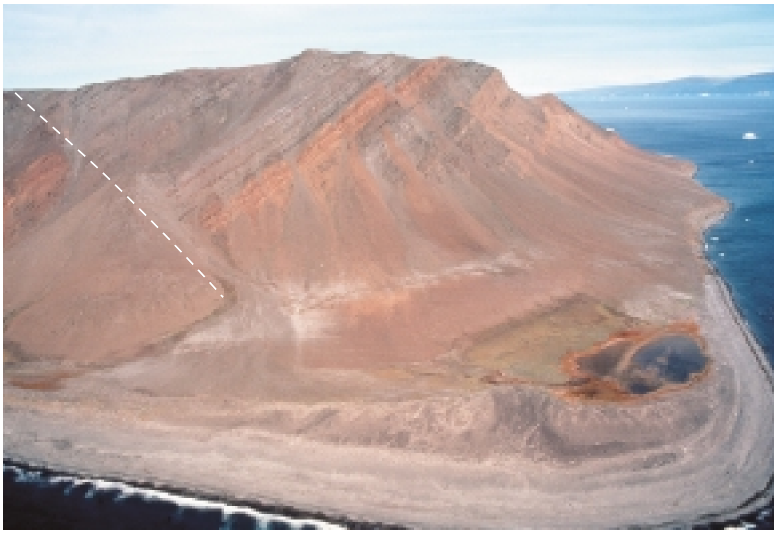
The structural studies were concentrated in areas around Bartschiakløft, Nuusap Sanningasua and Hareøen. Detailed studies were carried out in the Marraat area with special interest on the intense fracture and joint system in relation to the zeolite zonation. There is a correlation between intensity of mineralised veins, presence of dykes and zeolite zonation, as well as a difference in orientation between veins and joints with zeolite zonation and those without.

Structural profiles were made in the Nuusap Sanningasua area in order to study the relative chronology of dykes and veins in the area. It is possible to establish chronological relations between at least three generations of dykes and veins, where the youngest of the mineralised veins often appear to cut through clasts in the hyaloclastites (Fig. 5).

Systematic sampling of dykes at Nuusap Sanningasua was carried out in order to make a geochemical correlation between dykes and specific lava successions and to obtain absolute ages for the dykes. There is a close relationship between appearance of dykes and the concentration of calcite-filled veins in the hyaloclastites. Furthermore there is a difference in orientation of dykes between areas with joints and mineralised veins and areas without.

Structural studies in Bartschiakløft have revealed a complex system of faults that can be divided into at least three directions. Some fault trends, also visible on the offshore seismic data, may be related to the rifting phase of the opening of the Labrador Sea. Further studies and

Fig. 6. View of the 300 m high part of Hareøen showing an E–W trending fault displacing the lower part of the Vaigat Formation.



correlation between onshore structural data and offshore seismic data are necessary in order to establish a structural model for the development of the Nuussuaq Basin.

The stereo-photography programme referred to above was extended to areas around Sikillingi, Marraat, Bartschiakløft, Kuugannguaq and Hareøen (Fig. 6).

Studies of hydrothermal alteration

A new research programme was initiated in 1997 to assess the nature of hydrothermal alteration within the Tertiary lavas of Disko, Nuussuaq, and Hareøen. The main aims of this work are: (1) identification and mapping of regionally extensive depth-controlled secondary mineral isograds throughout the province; and (2) documentation, sampling, and mapping of hydrothermal veins and replacement alteration in the Marraat area. These objectives were met through regional-scale mapping and outcrop-scale observations and sampling.

Investigations of regional alteration patterns concentrated on identification of regionally extensive zones characterised by secondary mineral assemblages dominated by zeolites. Similar sets of zeolite zones have been observed in other parts of the North Atlantic Tertiary igneous province (e.g. Walker 1960a, b; Jørgensen 1984; Neuhoff *et al.* 1997) where they are sensitive indicators of the thermal (Kristmannsdóttir & Tómasson 1978) and lithological structure (e.g. Walker 1960a) of the upper crust. The zeolite zones indicate the palaeothickness of the now partly eroded Tertiary flood basalts in the province, and make it possible to interpret the geothermal gradient in the lava series shortly after the eruption of the basalts. Systematic mapping of zeolite zones along the south-western, southern, eastern and north-eastern coasts of Disko, south-western Nuussuaq and Hareøen indicates that most of the exposed lavas have undergone regional low-grade metamorphism (< 100°C based on the presence of the chabazite-thomsonite, analcime, and mesolite-scolecite zones) in response to geothermal gradients ≤ 30°C/km. Reconnaissance mapping along the southern coast of Nuussuaq west of the Itilli fault zone suggests that these lavas were altered at significantly higher temperatures (≥ 100°C based on exposures of laumontite and stilbite-heulandite bearing lavas) and tilted westward after regional metamorphism. Assuming that the geothermal gradient is ≤ 30°C/km, then the zeolite zones present in the area indicate an erosion factor less than expected.

Detailed outcrop and kilometre-scale investigations were conducted in order to determine the conditions, relative timing, structural environment, and relationship to oil migration of various stages of alteration present in the Marraat region. Early regional alteration (dominated by thomsonite with local development of chabazite and analcime) fills primary pore spaces in the lavas and is overprinted by several prominent vein sets. The most prominent of these veins in outcrop are filled with silicate-bearing (xonotlite, pectolite, or natrolite) mineral assemblages and occur together in infrequent swarms as reported by Karup-Møller (1969). Other less prominent but more common veins filled with quartz or calcite or both frequently post-date the silicate veins. Certain carbonate veins contain petroleum and appear to be conduits for migration; lavas hosting these veins are petroliferous and exhibit extreme CO_2 metasomatism that replaced (often pseudomorphically) earlier Ca-silicate alteration with silica-clay-carbonate assemblages.

Preliminary field results and planned analysis of samples collected in 1997 will provide fundamental data for assessing the physical and chemical nature of petroleum systems in West Greenland. Regional alteration patterns (i.e. zeolite zones) constrain the pre-erosional thickness of the lava pile, thermal gradients during regional alteration, and the timing and orientation of structural deformation within the lava pile (cf. Neuhoff *et al.* 1997) necessary for evaluating the burial and thermal history of the underlying sedimentary basin(s). Determination of vein mineralogy, orientation, frequency and timing promises to provide at least semi-quantitative constraints on the magnitude, direction and composition of groundwater migrating through the reservoirs. Lastly, the apparent spatial and causal relationships between petroleum-bearing veins and carbonate-metasomatism may offer a new exploration tool for identifying petroleum migration paths in basaltic reservoirs.

Commerical exploration by grønArctic Energy Inc.

Compared to the very active year of 1996 when grønArctic carried out a major airborne geophysical survey and drilled a *c.* 3 km deep exploration well, GRO#3, on Nuussuaq (see Christiansen *et al.* 1997), the level of commercial exploration activity was very low in 1997 and did not include any field work, geophysical surveys or drilling. In 1997 grønArctic gave up their license that covered 1011 km^2 on eastern Disko, together with a few valleys in central and northern Disko. By the end of 1997 grønArctic had relinquished further areas on Nuussuaq so the company's remaining licence area is reduced to 390 km^2.

Future work

Field work, analytical studies and regional interpretation of the development of the Nuussuaq Basin will continue in the coming years, and will include a variety of geological disciplines. Results from the sedimentological, structural, volcanic and zeolite minerals studies will add considerable knowledge to the understanding of the petroleum system of the Nuussuaq Basin, especially with respect to source and reservoir rocks and timing of trap formation and maturation.

Considerable analytical effort will be used to study the distribution and origin of the different oil types, and their implications for the exploration potential of the Nuussuaq Basin as well as for the neighbouring offshore basins. Additional field work may add new localities to the encouraging pattern that has been demonstrated so far. Infill sampling is necessary in some areas whereas areas without previous evidence of oil shows (e.g. on western Disko) will be checked. The presence of sediment-contaminated volcanic rocks with magma-modified carbon and sulphide-rich sedimentary xenoliths along the entire west coast of Disko indicates the existence of marine carbonaceous sediments beneath the basalts west of the Disko gneiss ridge over very large areas. This makes western and south-western Disko a natural target for systematic 'oil hunting' in the future.

Acknowledgements

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New structure maps over the Nuussuaq Basin, central West Greenland

James A. Chalmers, T. Christopher R. Pulvertaft, Christian Marcussen and Asger K. Pedersen

In 1992 the Geological Survey of Greenland (GGU) discovered bitumen in vugs and vesicles in Upper Paleocene basalts in western Nuussuaq (Christiansen *et al.* 1994). Since then the search for surface oil showings by GGU (from 1995 by the Geological Survey of Denmark and Greenland, GEUS) has resulted in finds over an area extending from northern Disko through Nuussuaq to the south-east corner of Svartenhuk Halvø (Christiansen *et al.* 1997, 1998, this volume). In addition, slim core drilling by GGU and grønArctic Energy Inc., the holder of an exclusive licence in western Nuussuaq, penetrated oil-saturated rocks at four localities (Christiansen *et al.* 1996). Encouraged by these results, grønArctic drilled a conventional exploration well (GRO#3) to 2996 m in 1996 (Christiansen *et al.* 1997), but details about this have not been released. The net effect of these efforts has been to dispel partially the formerly widespread view that the West Greenland area is entirely gas-prone and to promote the Cretaceous–Tertiary Nuussuaq Basin from being a model for what may occur in offshore basins to being a potential petroleum basin in its own right.

Evolving conceptions of the Nuussuaq Basin took a large step forward when GGU in 1994 acquired a 13 km 15-fold seismic line on the south coast of Nuussuaq (Christiansen *et al.* 1995). This showed a sedimentary section 6–8 km thick, much greater than the 2–3 km previously measured from onshore outcrops alone. This showed how little was understood about the structure of the basin, as well as where hydrocarbons might have been generated and where exploration could best be directed.

A first step to rectify this situation was taken in 1995 when multichannel seismic and gravity data were acquired by the Survey in Disko Bugt and the fjords north and south of Nuussuaq, as well as west of Disko (Christiansen *et al.* 1996). The new data have been integrated with older gravity, magnetic and seismic data from both onshore and offshore. This report summarises the results of interpretation of all available geophysical data together with a reappraisal of all available data on faults onshore. Detailed accounts are being published elsewhere (Chalmers 1998; J.A. Chalmers *et al.* unpublished data). Although the open spacing of the seismic lines and the almost total lack of reflections below the first sea-bed multiple on these lines make it impossible to present a definitive structural model at this stage, the structural style in the basin is now apparent and a number of the major structures in the area have been identified with confidence.

Geophysical data

The following geophysical data have been used in the interpretation presented in this report.

1. A 13 km long digital seismic line, GGU/NU94-01, along the south coast of Nuussuaq, acquired by GGU in 1994 using explosives as source and geophone detectors. Processing to stack stage only (Christiansen *et al.* 1995).

2. 711 km multichannel seismic data along eight lines in Disko Bugt, Vaigat and north of Nuussuaq (Fig. 1) acquired by the Survey in 1995 using the adapted high ice-class Danish Navy vessel *Thetis,* under charter to Nunaoil. Funding was provided by the Government of Greenland, Minerals Office (*now* Bureau of Minerals and Petroleum) and the Danish State through the Mineral Resources Administration for Greenland. The four lines in Disko Bugt were acquired using a 3 km digital streamer, but because of ice conditions in Vaigat and north of Nuussuaq only a 1200 m streamer could be deployed in these areas.

3. Single channel analogue seismic data and magnetic data acquired in 1970 by M.S. *Brandal* (Denham

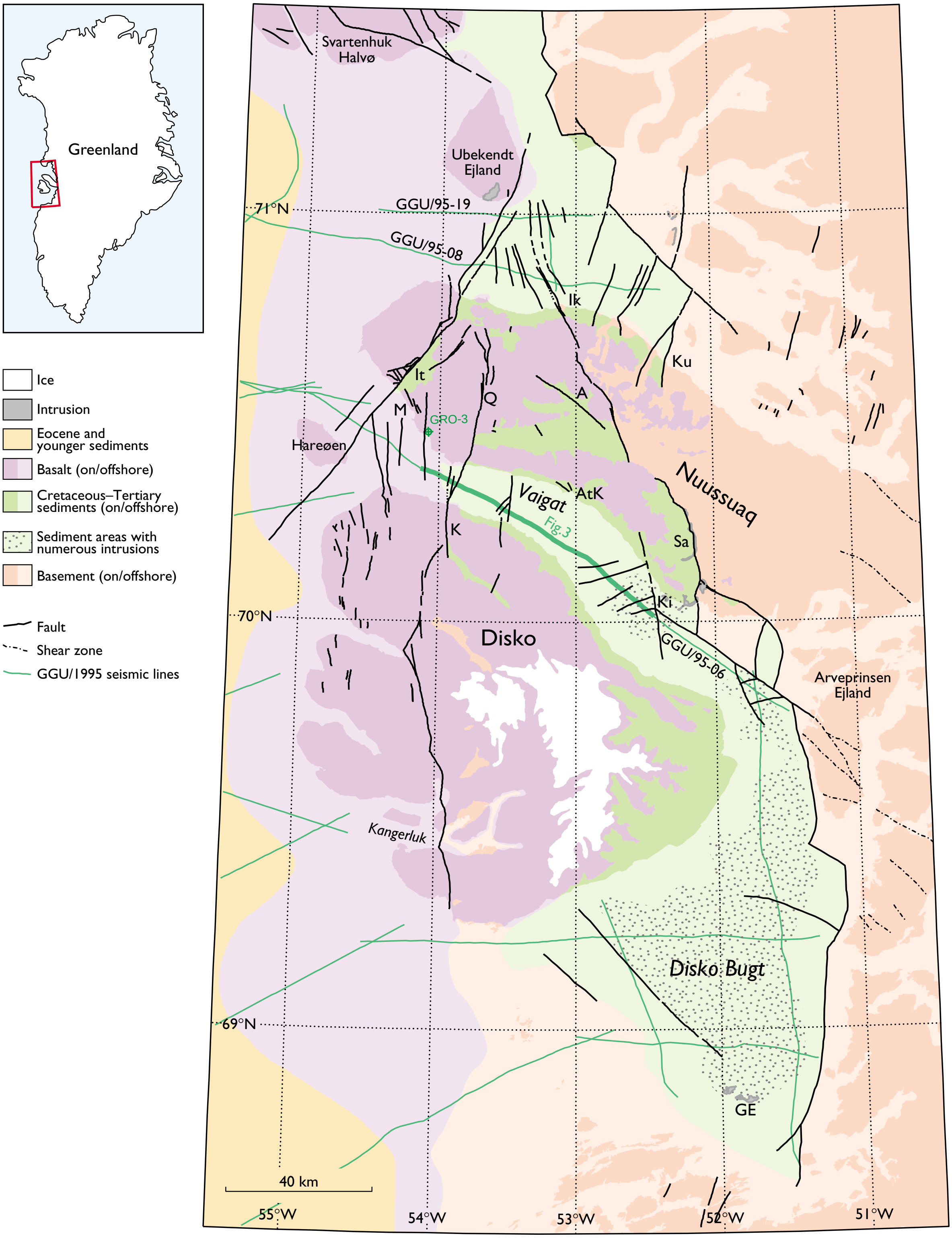

Fig. 1. Geological outcrop map (including outcrop at sea-bed) of the Disko–Nuussuaq area, showing also the position of the seismic lines acquired in 1995 and the GRO#3 well site. Place name abbreviations as follows: Ik: Ikorfat; Ku: Kuuk; It: Itilli; M: Marraat Killiit; Q: Qunnilik; AtK: Ataata Kuua; A: Agatdalen; Sa: Saqqaqdalen; K: Kuugannguaq; Ki: Kingittoq; GE: Grønne Ejland.

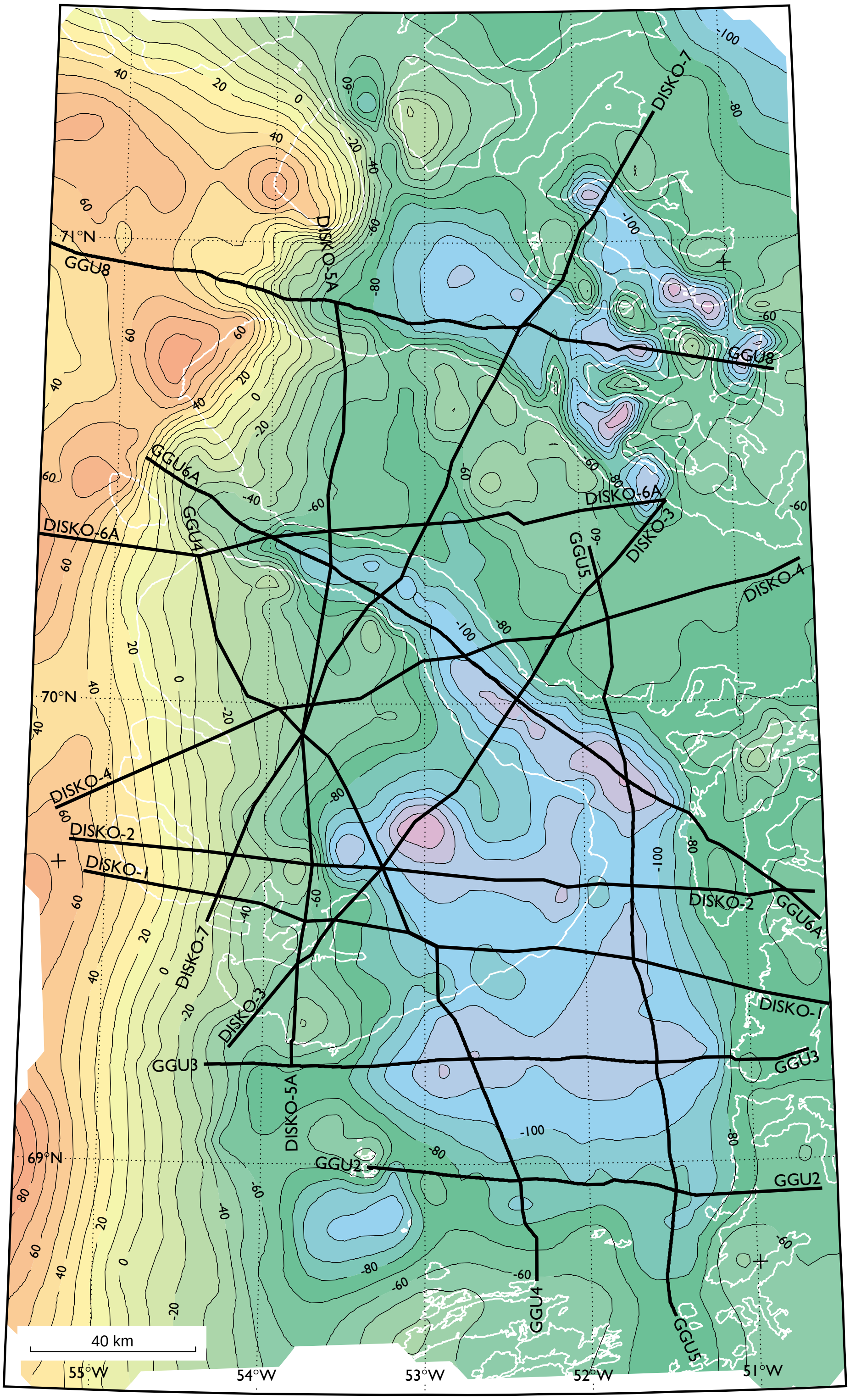

Fig. 2. Gravity anomaly map. Bouguer anomalies are shown onshore and free-air anomalies offshore. The labelled lines show the locations along which modelling was carried out to produce the depth to basement map shown in Figure 4. See Chalmers (1998) for details. Coastline shown by white lines.

1974) and in 1978 by M.V. *Dana* (Brett & Zarudski 1979). Navigation on *Dana* was by Transit satellites and Doppler sonar, but on *Brandal* only by dead reckoning and radar fixes of coastal features. There is thus an uncertainty of up to a few kilometres in the location of the *Brandal* profiles. The maximum depth of reflections that can be seen in the single channel data is about 500 metres.

4. Gravity data. New gravity data were acquired concurrently with the multichannel seismic data on the *Thetis* cruise. These data were integrated with all data in the archive of the Danish National Survey and Cadastre (KMS) to form a single data set (R. Forsberg, personal communication 1997). An anomaly map, shown in Figure 2, was then compiled using Bouguer anomalies onshore and free air anomalies offshore. Forward modelling of the gravity data was carried out along the lines also shown in Figure 2.

Seismic interpretation and mapping

The migrated multichannel data were interpreted on a Landmark work-station. The procedure adopted initially was to survey the profiles in detail by picking reflections without regard for their geological significance. During this procedure it was realised that, on the lines acquired using a 1200 m streamer, only very few real reflections were visible below the first sea-bed multiple. In Disko Bugt, where a 3 km streamer was deployed, many real reflections below the sea-bed multiple can be seen, but no unambiguous top basement reflector could be distinguished. In some areas it was not possible on the seismic data alone to distinguish between basement and basalt outcrops at sea-bed, but on the *Brandal* magnetic data the two areas are distinguished clearly. The basalt flows, and also dolerite sills, are generally reversely magnetised, while the basement gives a positive magnetic signature.

This initial procedure was supplemented by an examination of the single channel seismic data, on which boundaries between areas with outcrop of sediments and areas of crystalline rocks (basalt and basement) at sea-bed could be distinguished. Again, *Brandal* magnetic data were used to distinguish between basalt, basement and sills. With the onshore geological maps as further control, a simple sea-bed outcrop map was then prepared (Fig. 1).

Further interpretation of the multichannel seismic data, especially in areas of sediment, consisted of picking prominent unconformities, faults, dykes and sills, and sufficient sedimentary reflections to give a good image of the structure. The envelope of the deepest visible reflections was also picked to be used in the gravity modelling.

Supplementary examination of the single channel seismic data revealed several faults which could be tied to faults identified on the multichannel data. Furthermore, apparent dips in sediments in intersecting lines could be used to calculate true strike and dip of the beds.

Faults and related structures in the onshore area

An examination of all relevant maps, reports and field notes has been carried out with regard to locating faults in the onshore area. Some of the major faults had already been located, e.g. the Ikorfat–Saqqaqdalen fault (Ik–Sa, Figs 1, 4; Rosenkrantz *et al.* 1974; Pulvertaft 1989); others that appear on older maps (e.g. 1:500 000 sheet Søndre Strømfjord – Nûgssuaq) could not be substantiated. The main improvements in the new fault map arise from accurate field and photogrammetric mapping of the Tunoqqu Member and other distinctive contaminated basalt marker horizons in the Vaigat Formation, the lowest of the Paleocene volcanic formations in the area (Pedersen *et al.* 1996; A.K. Pedersen, manuscript maps). This has revealed a number of approximately N–S faults in western Disko and western Nuussuaq. The most important of these is the Kuugannguaq–Qunnilik fault (K–Q; Figs 1, 4), which has a post-Vaigat Formation downthrow to the west of 380 m in the south, decreasing to 200 m in central Disko, then increasing to 700 m in central Nuussuaq.

Another significant N–S trending fault with downthrow to the west runs just west of the GRO#3 well (Fig. 1); the net post-Vaigat Formation downthrow on this fault plus lesser faults to the west is of the order of 900 m.

In Agatdalen in central Nuussuaq there is a fault trending 125° which downthrows the Tunoqqu Member up to 300 m on the north-east side.

Two faults trending 124° and 161° have been observed on the south side of Nuussuaq west of Ataata Kuua (G. Dam, personal communication 1997). Both faults downthrow Upper Cretaceous sediments about 300 m to the north-east; neither fault displaces the Lower Paleocene Quikavsak Member nor the basalts above.

Another previously unrecorded fault crosses the south coast of Nuussuaq at Kingittoq. This has been drawn in a NNW direction to link with the Ikorfat–Saqqaqdalen fault in central Nuussuaq. The Cretaceous–Tertiary sediments at Kingittoq have been displaced by large landslides, so that the Kingittoq fault cannot be observed in outcrop, but a pre-basalt down-to-west fault is required because east of Kingittoq there are Cenomanian sediments dipping north-east (Croxton 1978), while to the west there are nearly horizontal Santonian – Lower Campanian sediments (Olsen & Pedersen 1991).

The Ikorfat–Saqqaqdalen fault is part of the Cretaceous boundary fault system in central West Greenland, so named because the fault system delineates the eastern margin of present-day outcrops of Cretaceous sediments in the area. At Ikorfat the displacement of the Tunoqqu Member by the fault is 500 m down to the west, while Lower Cretaceous sediments must be downthrown very much more than this.

The Ikorfat–Saqqaqdalen fault is linked to the Kuuk fault to the east by a ramp, in which the basement surface and overlying Upper Albian sediments dip 9–16° towards north and north-east and are overlain unconformably by almost horizontal Maastrichtian mudstones and extensive Paleocene basalts. The Upper Albian sediments were deposited in a succession of environments from fluvial through marine inner shelf and tidal estuarine to lacustrine deltaic, with no indication of a steep fault scarp to the east during sedimentation (Pulvertaft 1979; Midtgaard 1996). This is one of the indications that the area of Cretaceous sediments originally extended east of the boundary fault system. Three N–S to NNE–SSW trending faults, each with a downthrow of 350–400 m to the west, dissect the ramp.

The Itilli fault crossing Hareø and western Nuussuaq is the only major fault in the exposed area with a NE–SW trend. The maximum vertical displacement on the Itilli fault is more than 3000 m down to the north-west, but much of this is uplift confined to the axial zone of an eastward-plunging anticline on the south-east side of the fault. It has been suggested that the Itilli fault is a left-lateral splay of the Ungava Fracture Zone to the west and south-west (Chalmers *et al.* 1993).

Sub-surface structure offshore interpreted from seismic data

East, south and west of Disko

Basement is exposed at sea-bed south of Disko and around the margins of Disko Bugt (Fig. 1). To the south-west and west of Disko, basalts are exposed on the sea floor; farther to the west these become covered by Eocene and younger sediments.

In much of Disko Bugt, two different facies can be seen on the multichannel lines. Locally, units up to a few hundred metres thick contain continuous and strong reflections (facies 1). Over larger areas, there are only weak and discontinuous reflections from within the sediments (facies 2). Both facies are interrupted by numerous faults of no great throw. The Cretaceous Atane Formation, exposed onshore (Pedersen & Pulvertaft 1992), is either dominated by fairly monotonous fluvial sandstones which could give rise to facies 2, or consists of alternating mudstones, sandstones and coals laid down in a fluvio-deltaic environment, which could give rise to facies 1.

In places there are strong discontinuous reflections which are often reversely magnetised and so probably indicate sills and dykes similar to those exposed in Saqqaqdalen on Nuussuaq and on Grønne Ejland in southern Disko Bugt. The areas within which these reflections commonly occur are shown in Figure 1 with an overprint.

Vaigat

Facies 2 is also present at sea-bed in much of the south-eastern third of Vaigat, except at the south-eastern end where a small graben contains over 1500 m of facies 1. No fault that could be an extension of the Saqqaqdalen fault into Vaigat is visible on the seismic lines, so it is shown in Figure 1 as being terminated to the south by a fault that strikes about 120° along eastern Vaigat; this fault is indicated on *Brandal* seismic lines and is also modelled on gravity profiles.

North-west of the south termination of the Saqqaqdalen fault, the structural pattern visible on seismic line GGU/95-06 is different. Sections of facies 1 over 2 km in thickness are visible, dipping eastwards in fault blocks separated by faults with downthrow to the west (Fig. 3). Intersecting single channel lines show the shallowest parts of these reflections in many places and this has enabled several true dips to be calculated, the resulting values being 5°–18° towards north-east and east. The location of the faults that separate the fault blocks can also be seen on the single channel lines, enabling the faults to be mapped. Some of these faults are known onshore.

North-west of shot-point (S.P.) 6350 on seismic line GGU/95-06 (Fig. 3) basalts are exposed at sea-bed. In the GRO#3 well the base of the basalts is 294 m below sea level (Christiansen *et al.* 1997), and approximately offshore Marraat Killiit, where the first discovery of an oil seep was made, the basalts are only about 300–500 metres thick; below the basalts eastwards-dipping reflections can be seen.

North of Nuussuaq

North of Nuussuaq, reflection patterns similar to those visible in Vaigat can been seen. East of the offshore extension of the Itilli fault, fault blocks containing more than 2 km of facies 1 sediments (here most likely marine) are separated by faults that throw down to the west. Basalt is exposed at sea-bed along the west side of the Itilli fault extension. North of seismic line GGU/95-19, basement, sediments and basalt have been mapped on the sea-bed using the single channel seismic and magnetic lines.

Deep structure from gravity interpretation onshore and offshore

Modelling techniques

Modelling of the gravity data proved to be difficult and ambiguous and a detailed description of the techniques used, problems encountered and results obtained is provided by Chalmers (1998). Only a summary is given here.

Attempts at identifying a regional gravity field by interpolating between the observed gravity values over areas of known basement were ambiguous and inconclusive, so models that included the crust–mantle transition were calculated. Where basement is known to be exposed, the only spatial variable is the depth to Moho, which was adjusted until a satisfactory agreement between modelled and observed fields was obtained.

Gravity profiles were constructed along the seismic lines plus extensions for several tens of kilometres into areas where basement is exposed, either onshore or at the sea-bed as in the area south of Disko. Additional profiles were constructed from gravity observations that lie approximately along a straight line. The location of all these profiles is shown on Figure 2. Where possible, profiles were constructed in such a way that they passed over two areas of basement outcrop, in order to be able to interpolate the Moho (regional) profiles. However, there is no unambiguous calibration of the profiles west of the Disko gneiss ridge (Fig. 4), over western Nuussuaq and north of Nuussuaq. In these areas it is necessary to *extrapolate* in some way the regional gravity field (depth to Moho) from where it is constrained. The models in

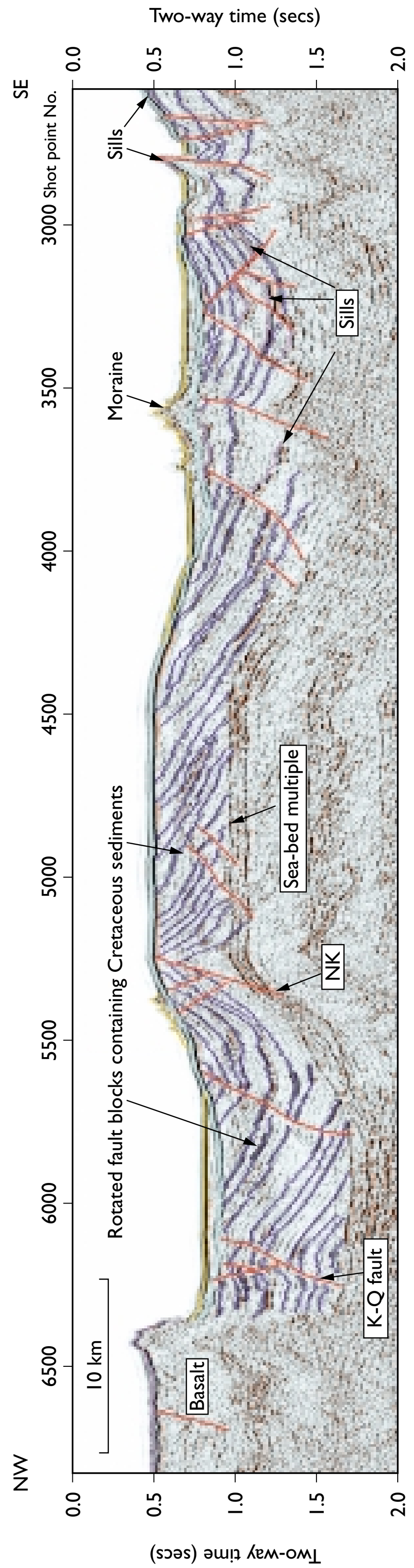

Fig. 3. Part of seismic line GGU/95-06 (outer part of Vaigat; Fig. 1). Facies 1 sediments (see text) can be seen separated into fault blocks, and the seismic response of basalts at sea-bed, a moraine, and sills can also be seen. K–Q: Kuugannguaq–Qunnilik fault; NK: a fault offshore Nuuk Killeq on the south coast of Nuussuaq where the subsurface of the hyaloclastite breccias drops about 400 m to the west in a monoclinal flexure (Pedersen *et al.* 1993). Red lines are faults

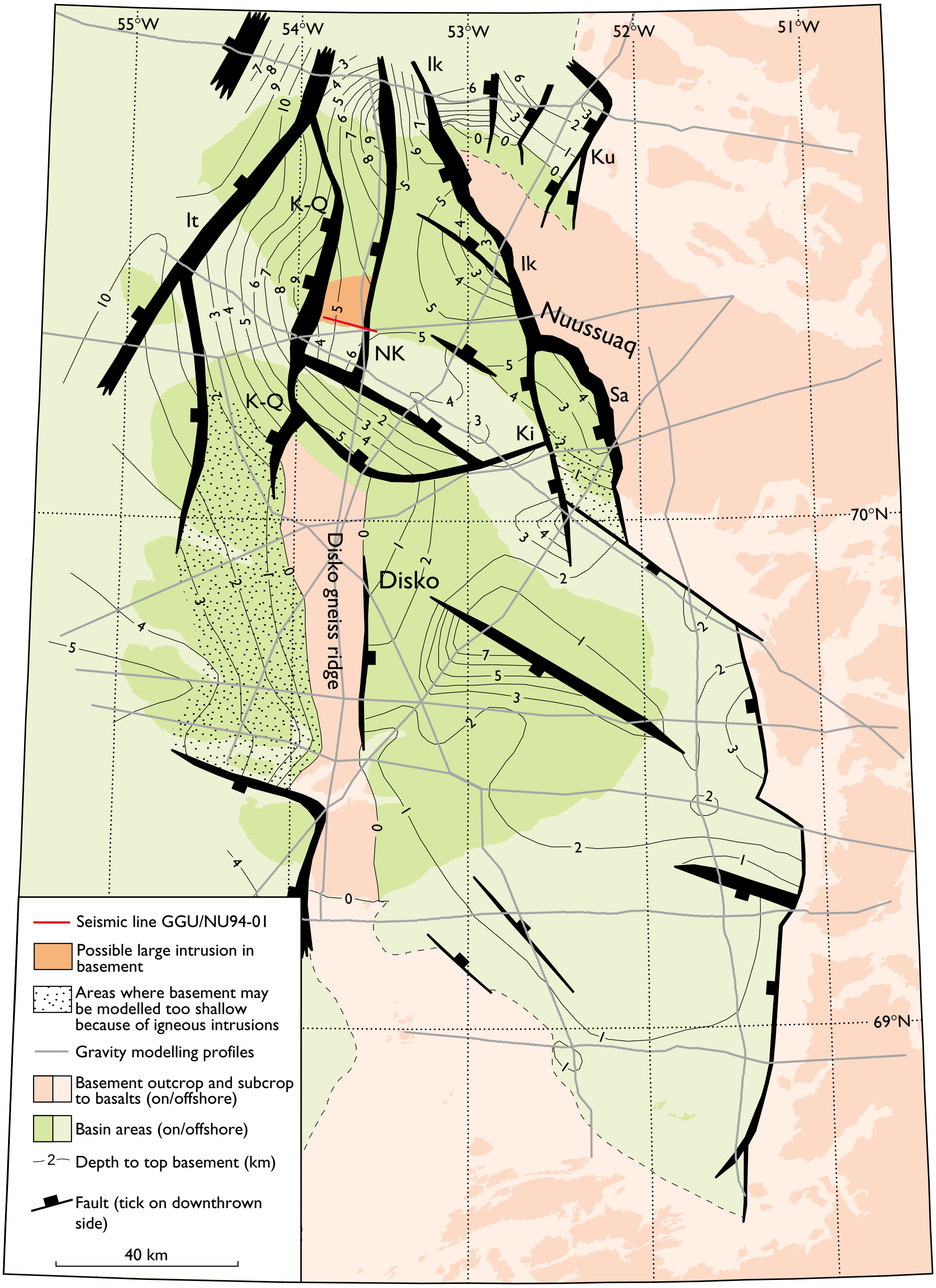

Fig. 4. Map of one interpretation of depth to basement obtained by forward modelling of gravity data along the profiles shown. Alternative interpretations are discussed in Chalmers (1998). Abbreviations on map as follows: It: Itilli fault; K–Q: Kuugannguaq–Qunnilik fault; Ik: Ikorfat fault; Sa: Saqqaqdalen fault; Ku: Kuuk fault; Ki: Kingittoq; NK: Nuuk Killeq, where the base of the hyaloclastite breccias drops 400 m to the west in a monoclinal flexure (Pedersen *et al.* 1993) and where a major fault can be seen on seismic line GGU/95-06 offshore (see Fig. 3). Width of fault symbol on map shows calculated heave.

these areas must therefore be treated circumspectly. Additional constraints on the gravity models are obtained from known outcrop limits of sediments, basement and basalts. A further constraint is the requirement that the modelled profiles should tie at their intersections.

Depth-converted interpretations from the multichannel seismic lines were used as starting points for modelling total sediment thickness, and in places the gravity model showed this to be depth to actual basement. However, in other places, lack of reflectivity in the deeper sedimentary section means that actual basement is deeper than 'acoustic basement'; where necessary, additional thicknesses of sediment were modelled until a satisfactory agreement between modelled and observed fields was obtained. In places, it was found necessary to make adjustments to the interpolated Moho profile in the basin areas.

The only constraint on the models west of the Disko gneiss ridge, over western Nuussuaq and north of Nuussuaq is the 13 km, 15-fold seismic line (GGU/NU94-01) on the south coast of Nuussuaq (Christiansen *et al.* 1995; Fig. 4). However interpretation of depth to basement on this line is ambiguous (Chalmers 1998) which means that two alternative models of depths to basement in north-western Disko, western Vaigat and western Nuussuaq have been produced, only one of which is shown here (Fig. 4).

Interpretation

Eastern Disko and Disko Bugt. Figure 4 shows depths to basement under eastern Disko and Disko Bugt to be generally less than 3 km. Depths to basement greater than 3 km are found only south-west of Arveprinsen Ejland and (possibly as great as over 7 km) under central Disko. However, the terrain in central Disko is alpine and capped with ice, so the somewhat simplified calculations carried out to produce the Bouguer anomalies mean that there may be considerable uncertainty in the accuracy of the gravity anomalies. The details of the modelling in this area are therefore very uncertain. The interpretation shown here implies the existence of a shallow basement ridge that strikes NW–SE under north-eastern Disko.

West of the Disko gneiss ridge. The modelling shows that the Disko gneiss ridge is bounded by faults to its north-west (the Kuugannguaq–Qunnilik fault (K-Q), which is known at outcrop) and south-west. The map in Figure 4 shows top basement dipping to the west at about 6°–10° from the central part of the ridge. It is difficult to reconcile the contours drawn through these lines with those drawn farther south, without either a fault or an area of steep contours, so a fault has been drawn striking 115°–120° under Kangerluk (Figs 1, 3).

Basalt thickness is controlled to within a few hundred metres from outcrop stratigraphy. However, it is possible that there are large numbers of Tertiary intrusions in the basement and sediments west of the Disko gneiss ridge, which would have the effect of raising its average density. In consequence, it is possible that the depths to top of basement west of the Disko gneiss ridge should be deeper than those shown on Figure 4. If so, it is possible that more of the western limit of the Disko gneiss ridge than shown here is formed by faulting, and that the Kuugannguaq–Qunnilik fault may continue southwards along the west margin of the ridge with larger throw at top of basement than is observed at basalt outcrop. In this case, the fault striking 115°–120° in Kangerluk is an artefact of the uncertainty in gravity modelling and has more to do with the intensity of igneous intrusions in the basement than with structure at top of basement. Areas where basement may be modelled too shallow because of igneous intrusions are shown on Figure 4 with an overprint.

Northern Disko, Vaigat, western Nuussuaq and north of Nuussuaq. The map shown in Figure 4 is one of two alternative interpretations of the gravity data. Space does not allow a detailed discussion of the alternatives here, and the interested reader is referred to Chalmers (1998).

Comparison of Figures 1 and 4 shows which faults are known at outcrop and which are modelled entirely from the gravity data. As discussed earlier, the gravity models are not well controlled in this area, and it is likely that many details will have to be revised as exploration proceeds. However, the general pattern of faults shown in Figure 4 is probably a reasonable approximation to the truth. In particular, there must be one or more faults that strike roughly NW–SE near the north-east coast of Disko that throw basement down from the Disko gneiss ridge to where thick sediments are known under Vaigat and Nuussuaq. These faults form a southern limit to an area where the sediments are generally much thicker than they are to the south and east.

Development of structure

The general trend of the fault system that marks the present-day boundary of sedimentary outcrops to the east is NNW–SSE, but components of this fault system also have WNW–ESE and *c.* N–S trends.

Within the basin, three main fault trends are evident. Firstly, a N–S trend is apparent. This especially defines the Disko gneiss ridge and its effect on the basalts shows that faulting with this trend was active at a late stage in basin development.

A second trend lies between WNW–ESE and NW–SE. This is the trend of several shear zones in the Precambrian basement east of Disko Bugt (Fig. 1), suggesting that these old shear zones exerted an influence on later faulting.

The third trend is NE–SW along the Itilli fault in western Nuussuaq that probably connects with the Ungava Fracture Zone farther south-west (Chalmers *et al.* 1993).

At present the sequence of events that created the Nuussuaq Basin is not entirely clear. There appears to be a deep basin under western Disko, western Nuussuaq and Vaigat that extends northwards beyond where it can be delineated by present data. There may also be a deep half-graben under central Disko east of the Disko gneiss ridge. A much more extensive and shallower basin extends over eastern Disko and Disko Bugt.

It is possible that the deep basin in the north-west is a rift basin, a hypothesis supported by the Moho being shallow in this area. In this case the more extensive, shallower basin could represent the thermal subsidence ('steer's head') phase of this rifting episode during which the Atane Formation was deposited.

These basins were then dissected by a new rift phase in the Maastrichtian and Early Paleocene (Rosenkrantz & Pulvertaft 1969; Pulvertaft 1989; Dam & Sønderholm 1998) which created the faults that form the present eastern limit of the basin, and faulted and rotated the facies 1 sediments into the fault blocks visible on line GGU/95-06 in Vaigat and on lines GGU/95-08 and GGU/95-19 north of Nuussuaq as well as onshore Nuussuaq. These faults trend between WNW–ESE and NW–SE, and N–S.

The rift blocks were eroded before being covered by Late Maastrichtian – Early Paleocene sediments and voluminous Late Paleocene basaltic lavas. These were in turn dissected during the Eocene by faults along a N–S (reactivated?) and a new NE–SW (Itilli) trend probably connected to plate tectonic movements of Canada relative to Greenland. This tectonic activity probably subsided during later Palaeogene times and the area appears to have been uplifted by 1–2 km during the Neogene to its present situation.

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A possible new hydrocarbon play, offshore central West Greenland

Nina Skaarup and James A. Chalmers

The discovery of extensive seeps of crude oil onshore central West Greenland (Christiansen *et al.* 1992, 1994, 1995, 1996, 1997, 1998, this volume; Christiansen 1993) means that the central West Greenland area is now prospective for hydrocarbons in its own right. Analysis of the oils (Bojesen-Koefoed *et al.* in press) shows that their source rocks are probably nearby and, because the oils are found within the Lower Tertiary basalts, the source rocks must be below the basalts. It is therefore possible that in the offshore area oil could have migrated through the basalts and be trapped in overlying sediments.

In the offshore area to the west of Disko and Nuussuaq (Fig. 1), Whittaker (1995, 1996) interpreted a few multichannel seismic lines acquired in 1990, together with some seismic data acquired by industry in the 1970s. He described a number of large rotated fault-blocks containing structural closures at top basalt level that could indicate leads capable of trapping hydrocarbons. In order to investigate Whittaker's (1995, 1996) interpretation, in 1995 the Geological Survey of Greenland acquired 1960 km new multichannel seismic data (Fig. 1) using funds provided by the Government of Greenland, Minerals Office (*now* Bureau of Minerals and Petroleum) and the Danish State through the Mineral Resources Administration for Greenland. The data were acquired using the Danish Naval vessel *Thetis* which had been adapted to accommodate seismic equipment.

The data acquired in 1995 have been integrated with the older data and an interpretation has been carried out of the structure of the top basalt reflection. This work shows a fault pattern in general agreement with that of

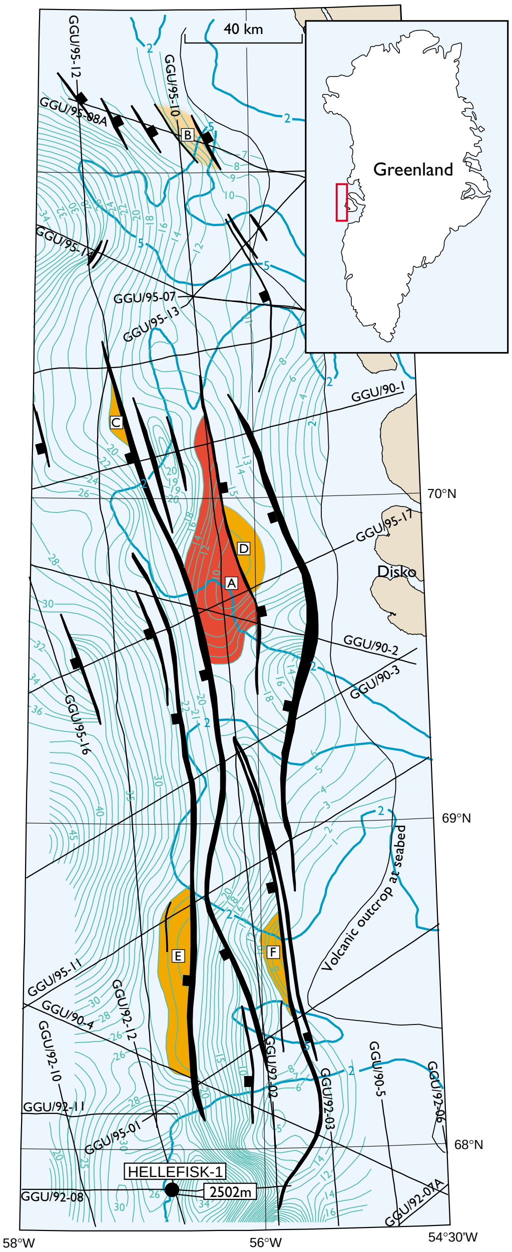

Fig. 1. Location map of the studied area showing the seismic lines, the five structural closures (structures A and C–F) and an additional lead (structure B), with structure A as the most prominent. Water depth shown by blue lines (only 200 and 500 m) and depth to top of the basalts by green lines (in hundreds of metres). The depth to the top of the Tertiary basalts at the Hellefisk-1 well is marked. Ticks on downthrow side of faults.

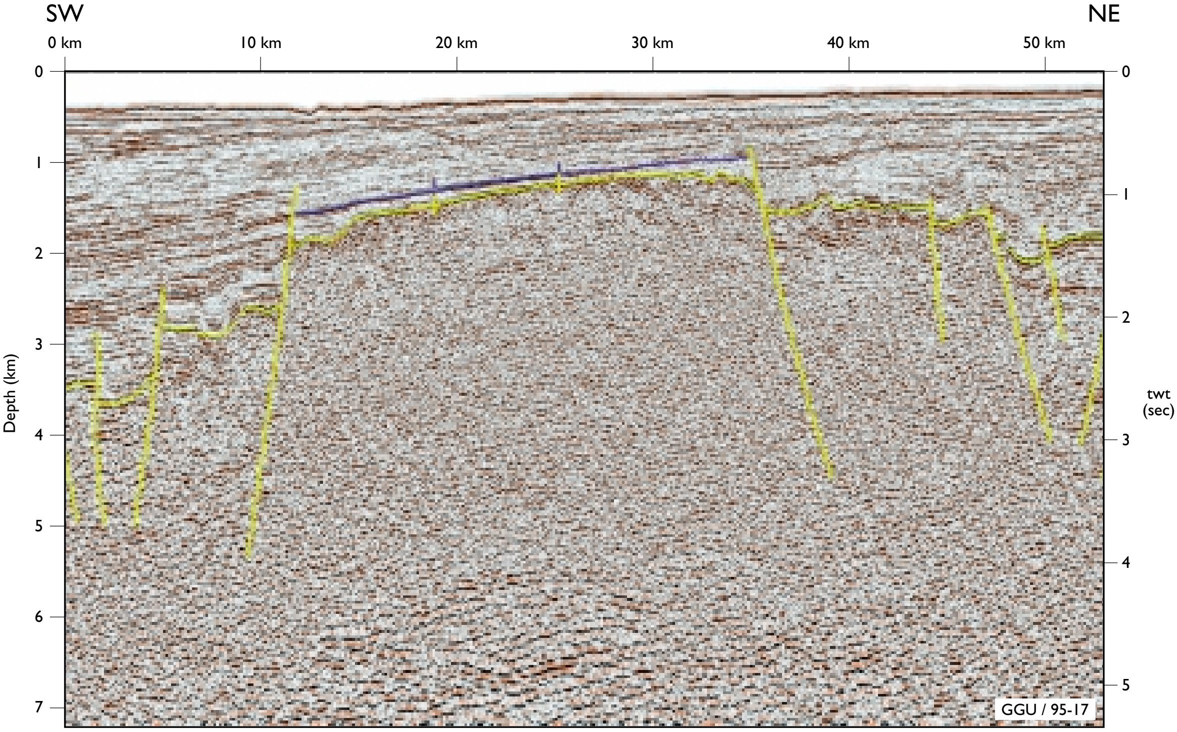

Fig. 2. Seismic section GGU/95-17 showing structure A as the horst block at top basalt level (yellow marker) bounded by faults to its east and west. Above the structure the 'bright spot' (blue marker) is shown. The post-basaltic sediments are seen to onlap structure A, indicating that deposition was controlled by topography. Below the centre of the structure some reflections are seen which are interpreted to be the base of the basaltic section. At depths of 5.5 km and 6.5 km strong reflections are seen which are tentatively interpreted to be from pre-basaltic sediments.

Whittaker (1995, 1996), although there are differences in detail. In particular the largest structural closure reported by Whittaker (1995) has not been confirmed. Furthermore, one of Whittaker's (1995) smaller leads seems to be larger than he had interpreted and may be associated with a DHI (direct hydrocarbon indicator) in the form of a 'bright spot'.

Interpretation

The seismic data used in this study were interpreted on a Sun work-station using Landmark SeisWorks-2D software.

The succession has been divided into intervals of different seismic character. The uppermost interval is present in most of the studied area, except east of 55°W where stratigraphically lower units crop out at seabed (Fig. 1). The uppermost unit is interpreted as sediments that can be tied to the Tertiary sediments in the Hellefisk-1 well (Rolle 1985). Throughout the study area the sediments lap onto top basalt level and indicate that the sedimentation was controlled by topographic structures (Fig. 2).

The top of the basalt unit is, except for the seabed, the most prominent reflector in the study area, and can also be tied to the Hellefisk-1 well (Rolle 1985). In many places reflections are visible from below the top of the basalts probably indicating that there are different seismic facies within the basalts and that sedimentary units may be found below the basalts. Work is continuing to determine the geological significance of the deeper, pre-top basalt reflections as well as the position of the base of the basalts.

Structure of the top basalt reflection

Whittaker (1995, 1996) showed that the top of the basalts is dissected by a complex system of steep, roughly N–S trending faults between 55°30′W and 57°W, south of 70°30′N. He suggested that this fault system consists of strike-slip faults related to oblique sea-floor spreading in Baffin Bay. The new data confirm Whittaker's (1995, 1996) interpretation in general terms. Steep faults with throws in places in excess of 1 km can be followed from seismic line to seismic line throughout most of the area

(Fig. 1). The faults define rotated blocks, and grabens have developed between the major faults. Complex minor faulting is commonly found within the grabens.

Farther north, the fault system shows a more NW–SE trend (Fig. 1). The coverage by 1990s data is very sparse in this area, but the older data used by Whittaker (1995, 1996) clearly shows this trend.

Prospectivity

Several structural closures at the top basalt level are shown on Figure 1 (structures A and C–F) and an additional lead (structure B) is indicated on the seismic lines.

The most promising structure, structure A, is situated west of Disko (Fig. 1). Structure A is bounded by faults to its east and west and closed by structural dip to the north and south. Figure 2 shows part of seismic line GGU/95-17 on which structure A can be seen as the horst block at top basalt level. Structural closure is mapped at about 1500 m depth and the shallowest part of the horst is at less than 1000 m depth. The structure is covered by 800–1300 m of sediments and approximately 200 m of water.

Above structure A a horizon within the sediments exhibits increased reflectivity (a 'bright spot'; Fig. 2) that approximately coincides with the structural closure mapped at top basalt level. The bright spot is seen on four seismic lines (Fig. 1) and is situated at a depth between 1000 and 1300 m below sea level, dipping from east to west. The bright spot has an extent of approximately 55 km in the N–S direction and from 7 to 23 km in the E–W direction, which gives an area of approximately 1000 km^2, so it could indicate the presence of large quantities of hydrocarbon. Preliminary results from an AVO (Amplitude Versus Offset) study on the bright spot on two seismic lines indicate that it is a Type 3 AVO anomaly in the sense of Castagna & Swan (1997), a typical gas-sand overlain by shale.

Several other small closures have been mapped and are shown and labelled on Figure 1. Whittaker (1995, 1996) mapped a large closure around the location of structure C in an area of sparse data coverage. Unfortunately the new data do not confirm Whittaker's (1995, 1996) mapping. Structure B can be seen on two seismic lines. However the structure is at the northern limit of seismic coverage, and there are no data to define its limits to the north. It is therefore unclear whether structure B is closed. All of these structures apart from B, are on the downthrown sides of faults, so their trapping potential is uncertain.

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Diagenesis and reservoir properties of Campanian–Paleocene sandstones in the GANT#1 well, western Nuussuaq, central West Greenland

Thomas Kierkegaard

As part of a study on reservoir characterisation of western Nuussuaq, central West Greenland (Sønderholm & Dam 1998) the diagenesis and reservoir properties of sandstone units in the GANT#1 well located in north-western Nuussuaq have been investigated (Kierkegaard 1998). The GANT#1 well was drilled during the summer of 1995 by grønArctic Energy Inc. (Calgary, Canada) as part of the company's hydrocarbon exploration activ-

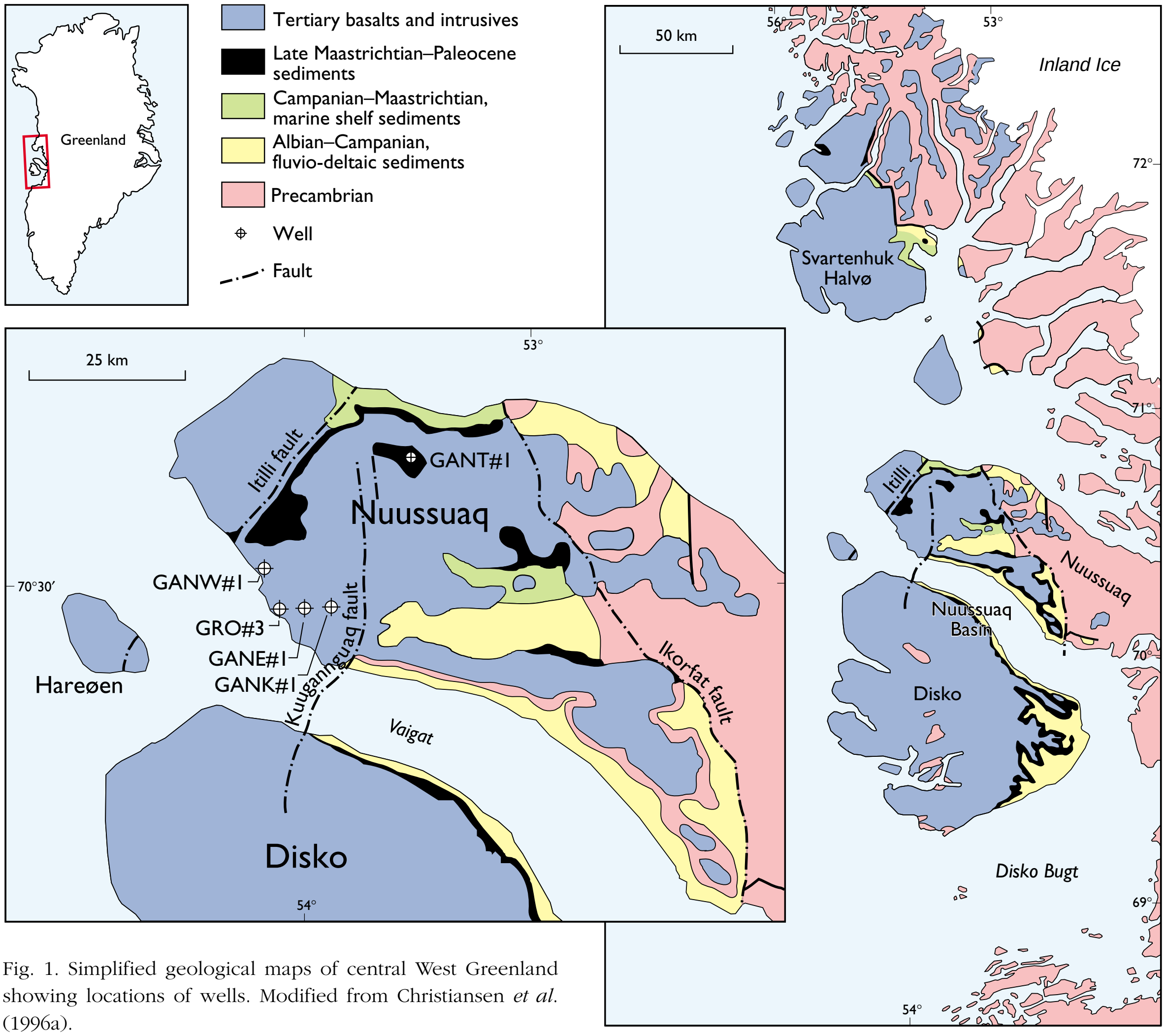


Fig. 1. Simplified geological maps of central West Greenland showing locations of wells. Modified from Christiansen *et al.* (1996a).

ities in the region. These also included the drilling of four other wells: GANW#1, GANE#1, GANK#1 and GRO#3 on the south-western coast of Nuussuaq (Fig. 1). The GANT#1 core was examined in order to elucidate the diagenetic and detritus factors that control the present porosity and permeability variations occurring in the Cretaceous – Lower Paleocene succession of western Nuussuaq. The examinations were carried out with standard petrographic methods, including X-ray diffractometry of mudstones and standard polarisation microscopy of thin sections from sandstones, supported by scanning electron microscopy (Kierkegaard 1998).

Porosity and permeability measurements from the GANT#1 core generally reveal poor reservoir quality with a range in porosity from 4.92 to 18.79% and in permeability from 0.106 to 90.7 mD, but both porosity and permeability are greater in post-Campanian sandstones compared to Campanian sandstones (Kierkegaard 1998). The GANE#1 well provides a section through Upper Paleocene turbiditic sandstone units alternating with mudstone units which thus furnishes a complementary and stratigraphically higher section to that found in GANT#1. However, porosity and permeability measurements from the GANE#1 well show low arithmetic average values of 6.4% and 1.46 mD, respectively (Andersen 1996).

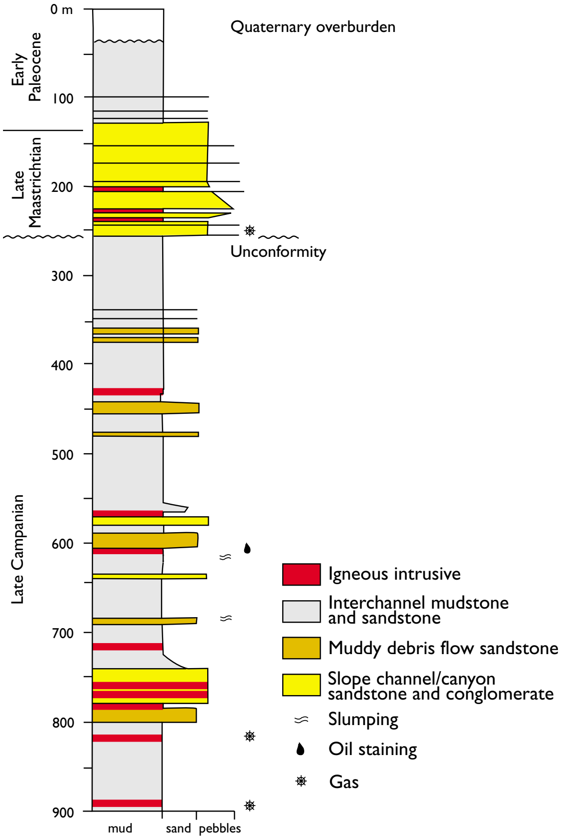


Fig. 2. Generalised sedimentological log from the GANT#1 core. Modified from Dam (1996).

Sedimentary environment

The West Greenland margin is a continental margin subdivided into linked basins where Cretaceous to Lower Tertiary, and probably older, sediments have been deposited (cf. Chalmers & Pulvertaft 1993; Dam & Sønderholm 1994). In the Nuussuaq area these sediments are overlain by an up to 2.5 km thick volcanic succession of Early Tertiary age (cf. Pedersen *et al.* 1993).

The GANT#1 well drilled through a 901 m succession of sediments which are penetrated by 15 small intrusions. A major, regional unconformity separates the upper 256 m, which include mudstones, coarse-grained sandstones and conglomerates of post-Campanian age, from a lower 646 m thick succession comprising mudstones and medium- to coarse-grained sandstones of Early to Late Campanian age (Fig. 2; Dam 1996; Nøhr-Hansen 1997).

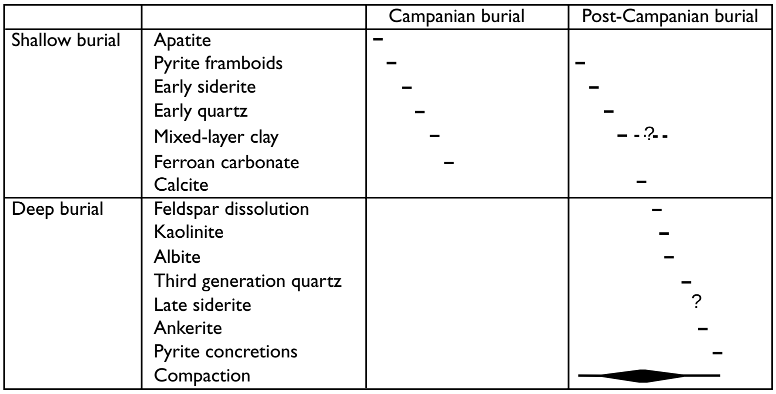
The vertical facies development suggests that deposition took place on a fault-controlled slope in canyons, major and minor distributary feeder channels, small turbidite lobes and interdistributary channel areas (Dam & Sønderholm 1994; Dam 1996).

Detrital composition of sandstones

The sandstones are classified as subarkoses and are generally poorly sorted; however, the post-Campanian sandstones above the unconformity seem to be better sorted and contain only little, if any, detrital clay. Feldspars are found both as unaltered and strongly sericitised grains and include both K-feldspar (mostly as microcline) and plagioclase generally in equal amounts. Lithic fragments are dominated by mudstone clasts. Compaction deformation, especially of the mudstone clasts, is the most significant alteration of the lithic fragments.

A slight difference in detrital composition between the Campanian and the Maastrichtian–Paleocene successions may represent a shift in provenance (Kierkegaard 1998).

Fig. 3. Paragenetic sequence of diagenetic events during the Campanian and Early Paleocene as observed in the GANT#1 well. Modified from Kierkegaard (1998).



Diagenetic alteration

The unconformity at a depth of 256 m in the GANT#1 well can be traced throughout the Nuussuaq Basin (Dam & Sønderholm 1998), and is interpreted as separating two distinct diagenetic stages of which the first only affects the Campanian deposits and the second the combined Campanian–Paleocene succession (Fig. 3; Kierkegaard 1998).

Organic maturity data indicate a shift from thermally immature to mature at around 350 m (Christiansen *et al.* 1996b) which parallels a change in mudstone composition from a succession dominated by smectitic illite/smectite to illite/vermiculite occurring between 270 and 400 m (e.g. Boles & Franks 1979; Burley *et al.* 1985). This suggests that the change in mudstone composition is probably related to burial diagenesis, a conclusion which is in agreement with most of the diagenetic alteration observed in the sandstones.

The Campanian diagenetic stage is characterised by growth of apatite, pyrite, siderite, quartz and mixed-layer clay, which all formed during shallow burial in a marine, eogenetic environment (Fig. 3; Kierkegaard 1998).

The shallow burial diagenetic changes were followed by cementation of the sandstone beds with ferroan carbonate forming conspicuous concretionary zones. These zones are only found in the Campanian sedimentary succession and are characteristically absent in the section overlying the unconformity. The amount of ferroan carbonate in the carbonate-cemented beds represents precement porosity and varies from 26 to 40%.

The development of the concretionary zones is probably related to the formation of the major erosional unconformity recognised at a depth of 256 m in the well (Fig. 2). This conclusion is supported by the fact that the zones only occur in the Campanian sandstone beds, and that oxygen and carbon stable isotopes suggest that they formed under the influence of meteoric water (Kierkegaard 1998).

Shallow Maastrichtian–Paleocene burial diagenesis is characterised by the development of pyrite, siderite, second generation quartz overgrowths, mixed-layer clay and calcite, which are all considered as phases developed in sediments influenced by evolved marine pore waters (Fig. 3).

Deeper burial diagenetic changes include feldspar dissolution and formation of secondary porosity followed by growth of kaolinite, albite, chlorite, third generation quartz, siderite, ankerite and concretionary pyrite. The changes affect both the post-Campanian sandstones and the Campanian sandstones which are not cemented by ferroan carbonate, and they mainly took place in detrital intragrain positions since most primary porosity was obliterated by compaction and the earlier diagenetic alterations (Kierkegaard 1998).

Reservoir conditions

Most of the present porosity in GANT#1 is secondary, originating from dissolution of detrital feldspar grains. However, growth of kaolinite, albite, quartz, siderite and ankerite all reduce this porosity. Formation of secondary porosity may not significantly have raised permeability, since most feldspar dissolution porosity in GANT#1 seems to be intragranular (cf. Ehrenberg 1990). There is, however, a marked difference in the degree of cementation between the Campanian and post-Campanian sandstones, as the Campanian contain relatively high amounts of authigenic mixed-layer clay and quartz (Kierkegaard 1998).

It is notable that although the post-Campanian sandstones contain only minor amounts of cement, permeabilities do not exceed 100 mD, implying that detritus is a major control on reservoir quality. This is supported by the poor sorting of the sediment, which reduces both porosity and permeability, and the high content of ductile mudstone clasts and siderite aggregates,which increase the degree of mechanical compaction (cf. Beard & Weyl 1973; Pittman & Larese 1991).

It is thus concluded that the rather poor reservoir quality generally characterising the sandstones of the GANT#1 core mainly results from compaction of a poorly sorted sediment containing ductile clasts, combined with precipitation of minor amounts of diagenetic minerals during shallow burial reducing primary porosity.

Although the reservoir properties of the sandstone intervals in the GANT#1 and GANE#1 wells are generally relatively poor, it is suggested that moderate to good properties may be found in certain intervals within the Maastrichtian–Paleocene succession. This conclusion is supported by petrophysical log evaluation of the GRO#3 well where the Paleocene sandstones show porosities between 10 and 15% and hydrocarbon saturations up to 50% (Kristensen & Dam 1997). However, the reason for the locally enhanced reservoir properties in GANT#1 was not clarified by this study, partly due to the lack of regional petrographic data.

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Petroleum geological activities in East Greenland in 1997

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In 1997, petroleum geological activities were continued in East Greenland in order to increase existing knowledge on the sedimentology and biostratigraphy of the Upper Permian – Mesozoic succession, and to better define and describe the petroleum systems of the basin. The activities form part of the multidisciplinary research project 'Resources of the sedimentary basins of North and East Greenland' initiated in 1995 with financial support from the Danish Research Councils, and were mostly continuations of pre- and post-doctoral research (Stemmerik *et al.* 1996, 1997). Some new activities were initiated during the 1997 season with financial support from Saga Petroleum a.s.a., Norway; they included an evaluation of the thermal effects and diagenetic changes resulting from Paleogene intrusions and a more detailed sedimentological study of the newly identified Jurassic succession of northern Hold with Hope (Stemmerik *et al.* 1997). Five teams worked in the region in July and August 1997 studying the Upper Permian – Lower Triassic of Wegener Halvø, northern Scoresby Land and Traill Ø, the Middle Jurassic – Lower Cretaceous of Hold with Hope and the Cretaceous of Traill Ø and Geographical Society Ø (Fig. 1). The work was logistically integrated with the Survey's other mapping activities in the region (see Henriksen 1998, this volume).

Upper Permian – Lower Triassic of Wegener Halvø

The study of the Upper Permian Foldvik Creek Group and the Lower Triassic Wordie Creek Formation of Wegener Halvø (Fig. 1) focused on the interplay between tectonic movements and sedimentation in the latest Permian to earliest Triassic. Facies mapping of the Upper Permian Foldvik Creek Group revealed a more complex pattern than suggested by Stemmerik (1979) and Stemmerik *et al.* (1989, 1993). The original model was a simple carbonate platform to shale basin transition with the shallow water facies distributed along the south-eastern side of the peninsula along Nathorst Fjord and the deeper water facies along the north-western, Fleming Fjord side. This simple proximal–distal facies distribution suggested deposition on a north-westward tilted fault block.

However, more detailed mapping shows that the peninsula is divided into two separate, north-westward tilted fault blocks. Thick shallow water carbonate successions of the Wegener Halvø Formation are located over the crests of the two fault blocks, respectively, along the Nathorst Fjord and in a NE–SW trend across the central part of the peninsula. The carbonates thin rapidly towards the north-west and thick successions of Ravnefjeld Formation shales are found in local subbasins. The two fault blocks continued to be important basin controlling structures also during the latest stages of the Permian where siliciclastic sediments dominated the basin fill. Shallow water sandy facies accumulated mainly over the fault crests whereas distal, shale-dominated facies were deposited in the deeper parts.

The Wegener Halvø area was uplifted in latest Permian or earliest Triassic times and up to *c.* 50 m deep and *c.* 550 m wide channels were eroded into the Permian strata. The channels are filled with a mixture of large blocks of Permian limestone and siliciclastic material. Sedimentation resumed during the Early Triassic (Griesbachian), and facies mapping of the Wordie Creek Formation shows that sedimentation was controlled by the same structural lineaments as influenced the Permian sedimentation. The thinnest and most proximal part of the Wordie Creek Formation is found towards the east-south-east on the relatively uplifted parts of the hanging wall. There, the formation is dominated by shoreface sandstones and coastal plain mudstones with evidence of periodic subaerial exposure. The formation becomes thicker (up to *c.* 380 m) and more fine grained towards the north-west, where it is dominated by offshore shales and turbidites.

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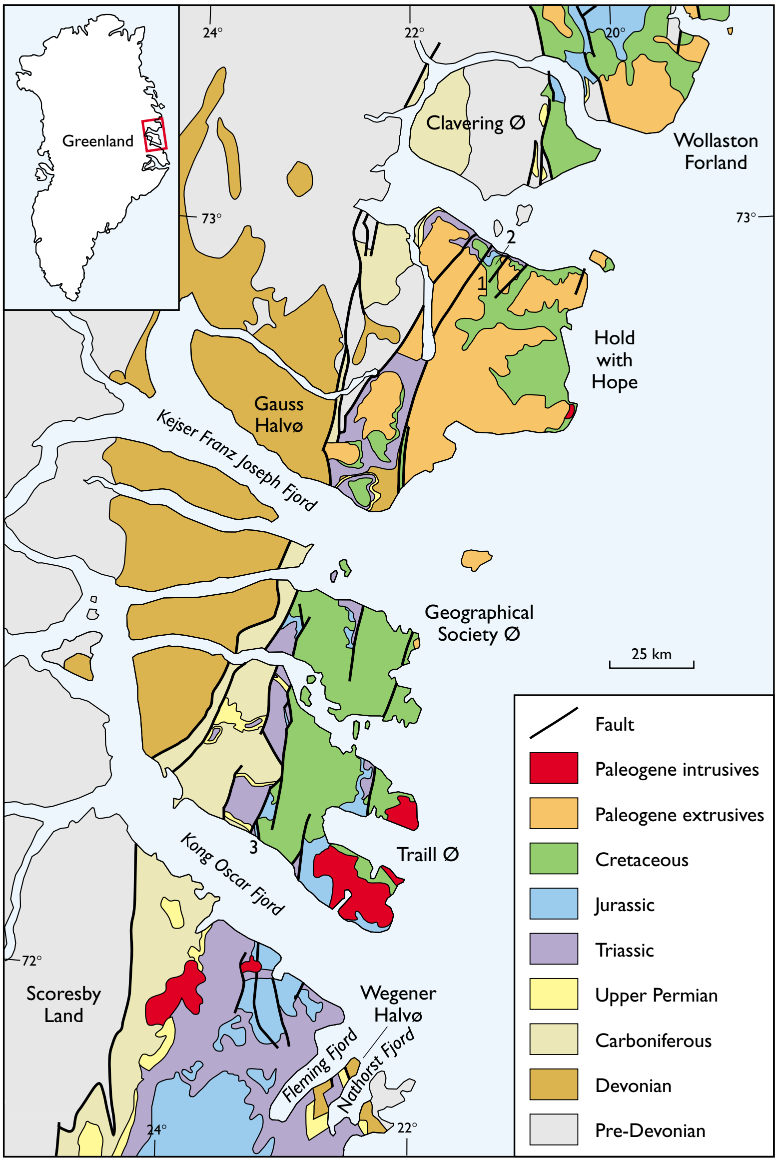


Fig. 1. Simplified geological map of part of East Greenland showing the distribution of Late Palaeozoic – Mesozoic sediments and Paleogene volcanic rocks. Numbers refer to localities mentioned in the text: 1, Gulelv; 2, Steensby Bjerg; 3, Svinhufvud Bjerge. Modified from Koch & Haller (1971).

In the offshore succession a network of incised valleys can be traced with drainage towards the west and north-west. This contrasts with earlier interpretations that stated valley directions were towards the south-west (Birkenmajer 1977). The valley fills consist of conglomerates and sandstones deposited mainly as sandy high density turbidites (Fig. 2).

One incised valley has been traced laterally and shows a change in valley width from *c.* 100 m up-dip to *c.* 565 m down-dip. This, in combination with a more gentle slope, resulted in deposition of a turbidite delta with prograding clinoforms of pebbly sandstones. The turbidite delta is 22 m thick and most likely thickens distally outside the outcrop area at the end of the slope. Deposition of the clastic turbidite system was controlled mainly by active faulting and an increase in sediment supply from the east. The fault activity induced a higher dip of the hanging-wall slope and exposure of the hanging-wall crest leading to erosion of the underlying Permian and older sediments.

The prograding turbidite deltas at the end of the hanging-wall dip slope form an important and hitherto poorly recognised reservoir analogue in the Lower Triassic succession. The turbidite deltas are composed

Fig. 2. Incised valley in the proximal reaches of the turbidite system in Wegener Halvø. The lower white bluff 30 m high consists of carbonate build-ups of the Upper Permian Wegener Halvø Formation (WHF). This is overlain by black shales of the Upper Permian Ravnefjeld Formation (RF). The shales are cut by an incised valley *c*. 250 m wide, filled with conglomerates and sandstones of the Triassic Wordie Creek Formation (WCF). Tents encircled for scale at top left.

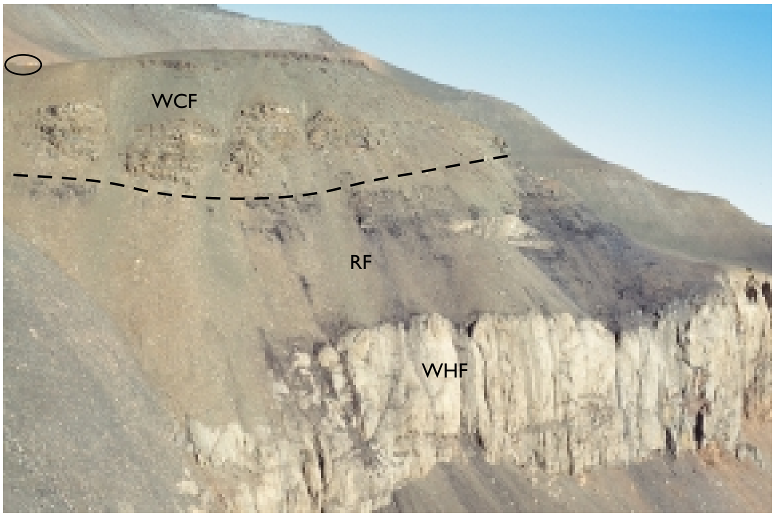
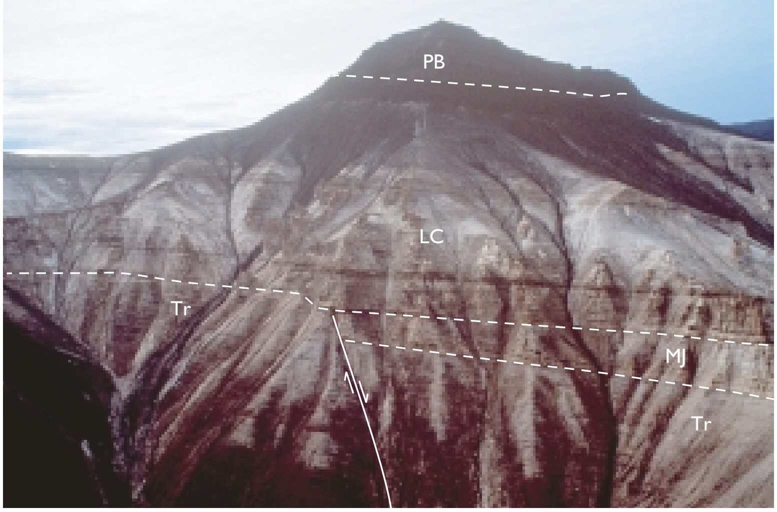


Fig. 3. The Triassic–Paleocene succession exposed at Steensby Bjerg in northern Hold with Hope (Fig. 1, loc. 2). The Triassic (Tr) and Middle Jurassic (MJ) sediments dip towards the south-west and are unconformably overlain by Lower Cretaceous (LC) sediments. Note the pre-Cretaceous normal fault which offsets the Triassic and Jurassic sediments. The exposure shown is *c*. 200 m high and topped by Paleocene basalts (PB). View towards the south.



of well-sorted sand encased in offshore shales acting as seal and cover large areas compared to the more stringer-like feeding channels found to the east.

Middle Jurassic – Lower Cretaceous of Hold with Hope

A coarse-grained sandstone succession was mapped in northern Hold with Hope in the summer of 1996 and dated to be of Middle Jurassic – Lower Cretaceous age (Stemmerik *et al*. 1997; Fig. 1). The Jurassic part of the succession was studied in more detail during the 1997 field season and new sections and studies of ammonite and dinoflagellate cyst stratigraphy show that the sediments also span the Late Jurassic (Oxfordian–Kimmeridgian).

The Jurassic sediments occur in small fault blocks dipping towards the west or south-west with the most complete succession preserved down-dip on the hanging-wall. Bedding planes within the Triassic and Jurassic successions seem to be parallel whereas they form an angular unconformity to the overlying Cretaceous succession (Fig. 3). This and the presence of normal faults cutting the Triassic and Jurassic succession, but stopping at the base of the Cretaceous, indicate that block rotation took place in post-Kimmeridgian but pre-Early Cretaceous time (Fig. 3).

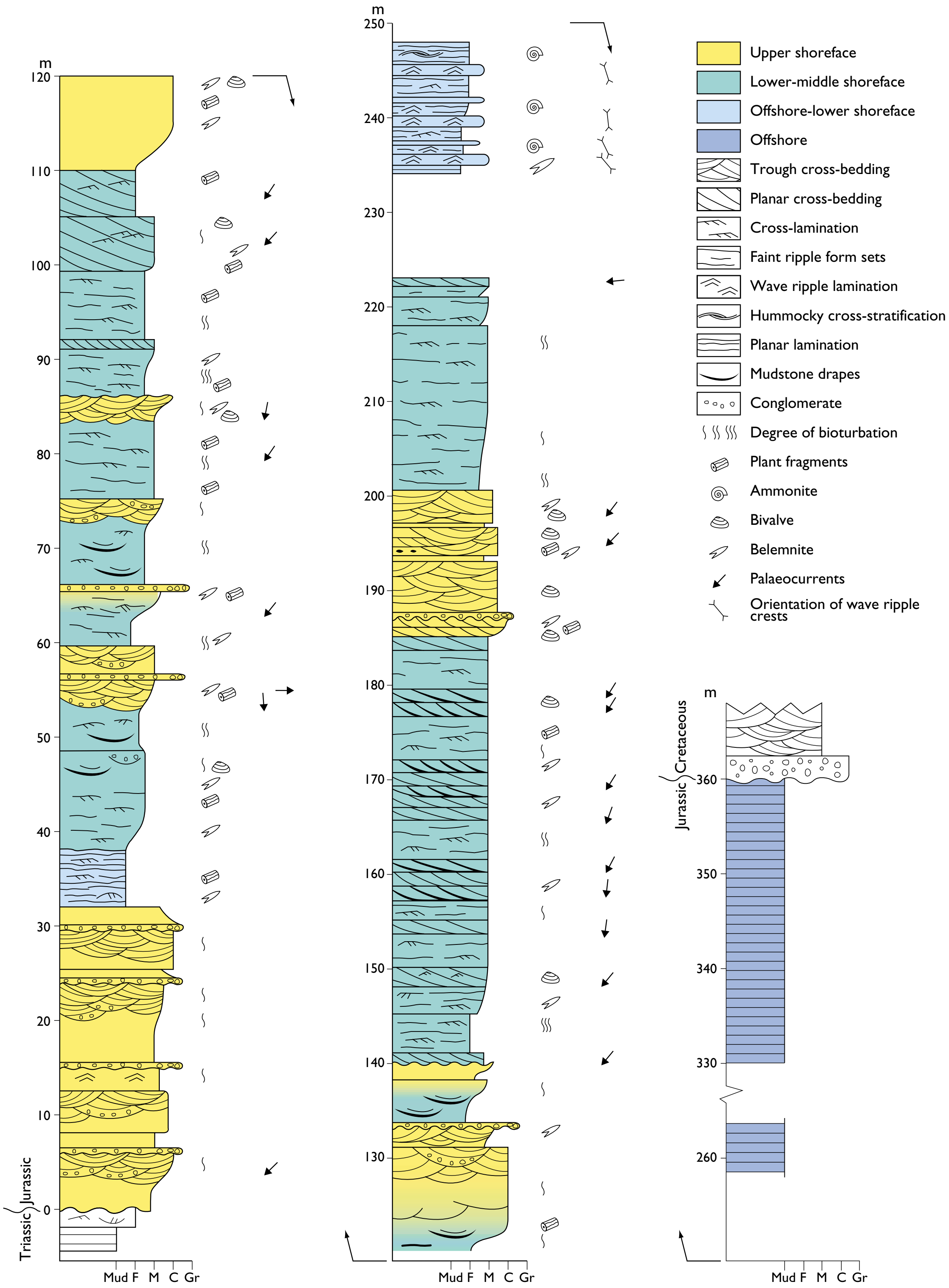


Fig. 4. Sedimentary section of the Middle–Upper Jurassic succession at Gulelv in northern Hold with Hope (Fig. 1, loc. 1). See text (opposite) for full explanation:

The thickest and most complete Jurassic succession, *c.* 360 m thick, is exposed in a fault block that dips *c.* 15° towards the south-south-west along the river Gulelv (Figs 1, 4). At this locality the basal *c.* 30 m of the succession consists of pebbly, medium- to coarse-grained quartz-dominated shoreface sandstones. The sandstones are trough cross-bedded or structureless and form coarsening-upward units, 6–8 m thick topped by a strongly bioturbated, pebbly sandstone lag.

A characteristic silty to very fine-grained, lower shoreface sandstone occurs 30–40 m above the base (Fig. 4). It is horizontally laminated, structureless or contains thin, subtle wave or current cross-laminated sandstones with thin organic-rich mudstone drapes. Coalified wood and belemnites are abundant and a single ammonite of Early Callovian age (P. Alsen, personal communication 1997) was found near the base.

The 40–250 m interval of the succession (Fig. 4) consists mainly of lower to middle shoreface wave- and current-rippled heteroliths and cross-bedded fine- to medium-grained sandstones with foresets separated by mud drapes or reactivation surfaces. Locally these deposits coarsen upwards into upper shoreface trough cross-bedded, coarse-grained sandstones showing palaeocurrents towards the south to south-west (Fig. 4). Belemnites and bivalves are common, and in the heteroliths silicified and coalified wood fragments, up to 1 m long, together with impressions of leaves are abundant. In places the heteroliths are strongly bioturbated. Ammonites of the Upper Oxfordian Glosense Zone (J.H. Callomon & P. Alsen, personal communications 1997) occur around the 240 m level.

The upper part of the succession consists of structureless or poorly exposed laminated offshore mudstones, and the thickness estimates are based mainly on simple geometrical calculations. The Jurassic succession on Hold with Hope closely resembles the Upper Bathonian – Kimmeridgian early syn-rift succession of the Wollaston Forland basin further to the north (Maync 1947; Surlyk 1977; Alsgaard *et al.* in press).

The overlying Lower Cretaceous sediments rest with an angular unconformity on the Jurassic. They consist of a conglomerate, locally up to 6 m thick, overlain by a thick deltaic and shallow marine sandstone succession, up to 150 m thick. These sandstones are trough cross-bedded, medium- to coarse-grained sandstones deposited as Gilbert-type deltaic units separated by marine flooding surfaces (see sedimentary section in Stemmerik *et al.* 1997). The sandstones are capped by mudstones of late Early Cretaceous age.

Diagenetic studies

Diagenetic studies were initially focused on the Middle Jurassic succession on Traill Ø and Geographical Society Ø, which forms a well-exposed analogue for reservoirs in the Norwegian offshore areas. The preliminary results of this study are outlined below. They indicate that the diagenesis is locally greatly influenced by the adjacent Paleogene intrusions, and therefore a new project was initiated during the 1997 field season to investigate more closely the thermal effects of Paleogene sills and dykes on diagenesis of Carboniferous to Cretaceous sediments. Published studies from other basins have mainly focused on the thermal effect on organic rich shales and have documented that the influenced zone roughly corresponds to the thickness of the intrusion (George 1992; Esposito & Whitney 1995). In order to investigate the diagenetic alteration of coarse-grained sediments, sandstones were collected with increasing spacing from the contact-metamorphic zone near the intrusion to a distance of two to three times the thickness of the intrusion. Reference samples of unaffected sediments were collected further away.

Coarse-grained sediments in contact with intrusions were found to be more resistant to weathering and often crop out in the terrain. The ability to resist weathering is due to a temperature-related cementation in the contact-metamorphic zone near the intrusion. This contact-metamorphic closing of the sandstone reservoirs near the intrusions could act as seals or barriers for fluid transfers in the reservoirs.

The diagenetic history of Middle Jurassic sandstones was investigated in samples from a 500 m thick succession at Svinhufvud Bjerge on the south coast of Traill Ø (Fig. 1, locality 3; Stemmerik *et al.* 1997). The lower part the succession is intruded by a 30–40 m thick Paleogene sill and it is cut diagonally by a 15 m thick dyke. The sandstones consist of quartz with minor feldspar, rock fragments, mica, clay matrix and traces of heavy minerals and are mostly quartz arenites and subarkoses *sensu* Folk (1968). However, most of the secondary porosity is derived from dissolution of feldspars and the pre-diagenetic composition of the sandstones was probably closer to subarkoses.

The main authigenic phases in the sandstones comprise quartz cement, carbonate cement, kaolinite and illite, while chlorite, titaniferous oxides and pyrite are minor components. Authigenic quartz occurs as euhedral crystals overgrowing detrital grains (Fig. 5A). The quartz partly encloses kaolinite and illite crystals indicating that it is synchronous with or post-dates kaolin-

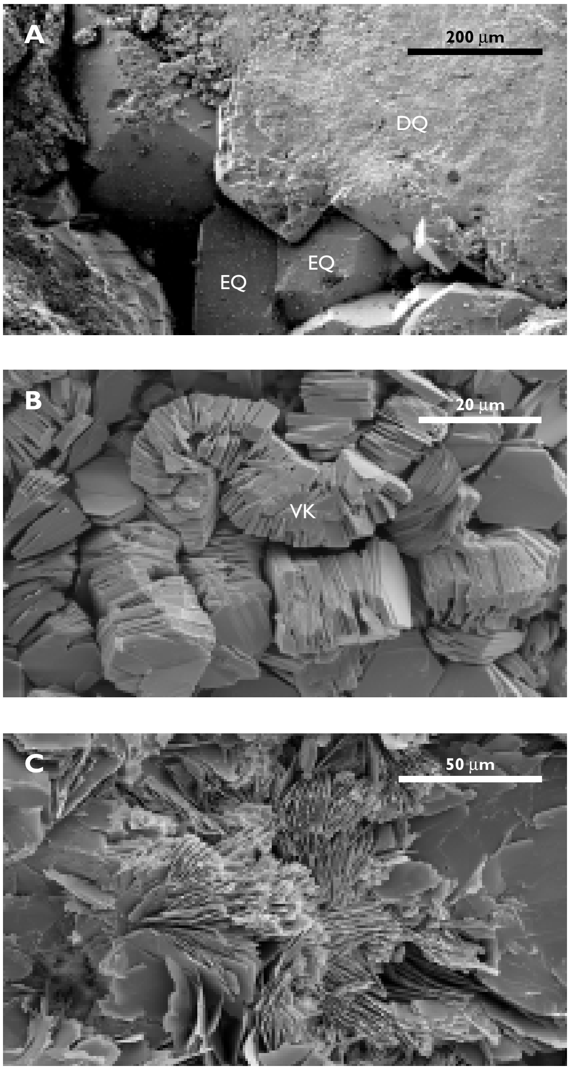


Fig. 5. Scanning electron photomicrograph of Middle Jurassic sandstones showing; **A**: large euhedral quartz overgrowths (EQ) developed on adjacent detrital quartz grains (DQ) resulting in nearly total occlusion of the porosity; **B**: vermiform kaolinite aggregate (VK) and booklets of kaolinite; **C**: large illite flakes in pore space. Photographs processed at: Acc. V; 10.0 kV; Spotsize: 5.0.

ite and illite. Kaolinite often occurs as pore-filling clusters of booklets or more rarely as vermiforms (Fig. 5B), whereas illite generally occurs as curving flakes with irregular edges (Fig. 5C), coating detrital grains and filling in pores. Illite is often seen densely packed in pore spaces (Fig. 5C) as well as large crystal flakes, up to *c.* 100 µm, scattered in the pore spaces or making up pseudomorphs. In a few isolated horizons carbonate cement consisting of calcite and dolomite-ankerite occludes pore space totally. Carbonate, however, most commonly occurs as isolated crystals of which some show dissolution and replacement by goethite.

Random vitrinite reflectance (R_o) analyses, Total Organic Carbon (TOC, wt%) and Rock-Eval pyrolysis (T_max) determinations were performed on coal samples from coarse-grained fluvial and finer-grained floodplain-lacustrine sediments. Coal from the fluvial unit show R_o values of approximately 4% and non-detectable T_max values indicating a very high maturation level (post-mature). In contrast analyses of the coals from the floodplain-lacustrine unit indicate a much lower maturation stage with R_o values around 1.1% (a single sample shows 1.74%) and T_max values in the range from 449°C to 461°C (mature stage).

Along with the coals both the fluvial mudstones and sandstones seem affected by heat from the nearby intrusions and hydrothermal fluids. This is seen as traces of talc and pyrophyllite in the mudstones just beneath the post-mature coals indicating very low-grade metamorphism (Frey 1987) and the presence of large illite crystals and illitised pseudomorphs in the sandstones. The differences in maturation and authigenic minerals between the fluvial and the floodplain–lacustrine unit may be a function of grain size. The sandstones in the finer grained floodplain–lacustrine unit have, thus, been protected and isolated from direct influence of hydrothermal fluids induced from the intrusions.

Petroleum systems

The petroleum geology of the region has previously been treated in a number of Survey studies (e.g. Surlyk *et al.* 1986; Christiansen *et al.* 1992; Stemmerik *et al.* 1993). The new data gained from the current field work may be used to improve the understanding of the petroleum systems in East Greenland. The Upper Jurassic petroleum system is based on the petroleum generating potential of the marine shales of the Bernbjerg Formation (Fig. 6). The formation is well known from the southern part of the area on Traill Ø and has previously been suggested to occur in the subsurface of eastern Hold with Hope (Stemmerik *et al.* 1993). In the 1997 field season Upper Jurassic shales with a fair source potential (TOC around 2%) were mapped out for the first time in the area around Gulelv on Hold with Hope.

The petroleum system has previously included Middle Jurassic sandstones of the Pelion Formation as the main reservoir unit. The work in the Hold with Hope area,

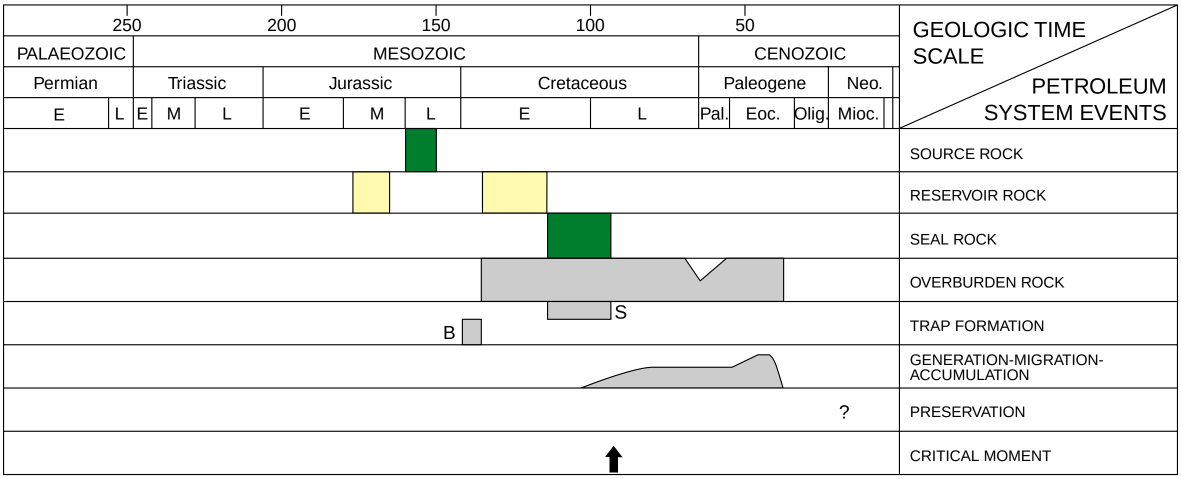


Fig. 6. Preliminary interpretation of the Upper Jurassic (Bernbjerg Formation) petroleum system in the northern part of the region following the terminology of Magoon & Dow (1994). Letters designate trap forming process, B; block faulting and rotation; S: stratigraphic pinch-out. The interpretation is based on data in Upton *et al.* (1980), Christiansen *et al.* (1992), Stemmerik *et al.* (1993), Price & Whitham (1997) and the present field work.

however, shows that the initial thickness of this reservoir unit may be highly reduced or it may be totally absent due to block rotation and erosion in the Late Jurassic – earliest Cretaceous (Fig. 3). Thick Lower Cretaceous sandstones exposed in Hold with Hope may, however, form an excellent reservoir unit, which has not been considered in previous studies. The fluvial, deltaic and shallow marine nature of these sandstones may suggest that coarse-grained sediments have been deposited in basins further east or south-east on the East Greenland shelf.

The new data also influence the previously suggested play model for the Middle Jurassic reservoir sandstones based on structural traps (Stemmerik *et al.* 1993; Price & Whitham 1997). The down-faulted Jurassic sandstones on Hold with Hope are thus not sealed by onlapping Cretaceous mudstones as seen on Traill Ø and Geographical Society Ø and a potential hydrocarbon play will depend on the presence of stratigraphic traps in the Lower Cretaceous. The succession in Hold with Hope probably formed in a platform or terrace area with an episodic depositional history and thus differs from the better known basinal areas further south.

Little is presently known on the possible generation, migration and accumulation history of hydrocarbons in the region, but ongoing studies aim at a better understanding of these processes. Thermal effects of Paleogene intrusions are, thus, important in the maturation history and have locally led to over-maturation of the otherwise immature source rock (Stemmerik *et al.* 1993).

Future work

The appraisal of petroleum systems helps to identify areas where further research is needed. In the 1998 field season petroleum geological research will focus on the Upper Cretaceous – Lower Paleocene (pre-basaltic) succession as an analogue to offshore northern North Atlantic basins. Geological mapping of the Upper Palaeozoic – Mesozoic succession is planned to take place on Clavering Ø, Gauss Halvø, Geographical Society Ø and the easternmost parts of Traill Ø. The study of the thermal effects of Paleogene dykes and sills will continue with field work on Traill Ø and Geographical Society Ø. The sandstones will be subjected to petrographic investigations to reveal the diagenetic changes and their effect on reservoir quality. Further investigations on both mudstones and sandstones will show whether mineral assemblages can be related to the distance from the intrusion and thereby determine the width of the reaction zone and the thermal regime of the intrusion.

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Sequence stratigraphy of source and reservoir rocks in the Upper Permian and Jurassic of Jameson Land, East Greenland

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Approximately half of the hydrocarbons discovered in the North Atlantic petroleum provinces are found in sandstones of latest Triassic – Jurassic age with the Middle Jurassic Brent Group, and its correlatives, being the economically most important reservoir unit accounting for approximately 25% of the reserves. Hydrocarbons in these reservoirs are generated mainly from the Upper Jurassic Kimmeridge Clay and its correlatives with additional contributions from Middle Jurassic coal, Lower Jurassic marine shales and Devonian lacustrine shales. Equivalents to these deeply buried rocks crop out in the well-exposed sedimentary basins of East Greenland where more detailed studies are possible and these basins are frequently used for analogue studies (Fig. 1).

Investigations in East Greenland have documented four major organic-rich shale units which are potential source rocks for hydrocarbons. They include marine shales of the Upper Permian Ravnefjeld Formation (Fig. 2), the Middle Jurassic Sortehat Formation and the Upper Jurassic Hareelv Formation (Fig. 4) and lacustrine shales of the uppermost Triassic – lowermost Jurassic Kap Stewart Group (Fig. 3; Surlyk *et al.* 1986b; Dam & Christiansen 1990; Christiansen *et al.* 1992, 1993; Dam *et al.* 1995; Krabbe 1996).

Potential reservoir units include Upper Permian shallow marine platform and build-up carbonates of the Wegener Halvø Formation, lacustrine sandstones of the Rhaetian–Sinemurian Kap Stewart Group and marine sandstones of the Pliensbachian–Aalenian Neill Klinter Group, the Upper Bajocian – Callovian Pelion Formation and Upper Oxfordian – Kimmeridgian Hareelv Formation (Figs 2–4; Christiansen *et al.* 1992).

The Jurassic sandstones of Jameson Land are well known as excellent analogues for hydrocarbon reservoirs in the northern North Sea and offshore mid-Norway. The best documented examples are the turbidite sands of the Hareelv Formation as an analogue for the Magnus oil field and the many Paleogene oil and gas fields, the shallow marine Pelion Formation as an analogue for the Brent Group in the Viking Graben and correlative Garn Group of the Norwegian Shelf, the Neill Klinter Group as an analogue for the Tilje, Ror, Ile and Not Formations and the Kap Stewart Group for the Åre Formation (Surlyk 1987, 1991; Dam & Surlyk 1995; Dam *et al.* 1995; Surlyk & Noe-Nygaard 1995; Engkilde & Surlyk in press). The presence of pre-Late Jurassic source rocks in Jameson Land suggests the presence of correlative source rocks offshore mid-Norway where the Upper Jurassic source rocks are not sufficiently deeply buried to generate hydrocarbons. The Upper Permian Ravnefjeld Formation in particular provides a useful source rock analogue both there and in more distant areas such as the Barents Sea.

The present paper is a summary of a research project supported by the Danish Ministry of Environment and Energy (Piasecki *et al.* 1994). The aim of the project is to improve our understanding of the distribution of source and reservoir rocks by the application of sequence stratigraphy to the basin analysis. We have focused on the Upper Permian and uppermost Triassic–Jurassic successions where the presence of source and reservoir rocks are well documented from previous studies. Field work during the summer of 1993 included biostratigraphic, sedimentological and sequence stratigraphic studies of selected time slices and was supplemented by drilling of 11 shallow cores (Piasecki *et al.* 1994). The results so far arising from this work are collected in Piasecki *et al.* (1997), and the present summary highlights the petroleum-related implications.

Source and reservoir rocks in a sequence stratigraphic framework

Sequence stratigraphic concepts have greatly improved our understanding of the genetic, spatial and stratigraphic distribution of depositional units, including source and reservoir rocks. Accordingly, such studies

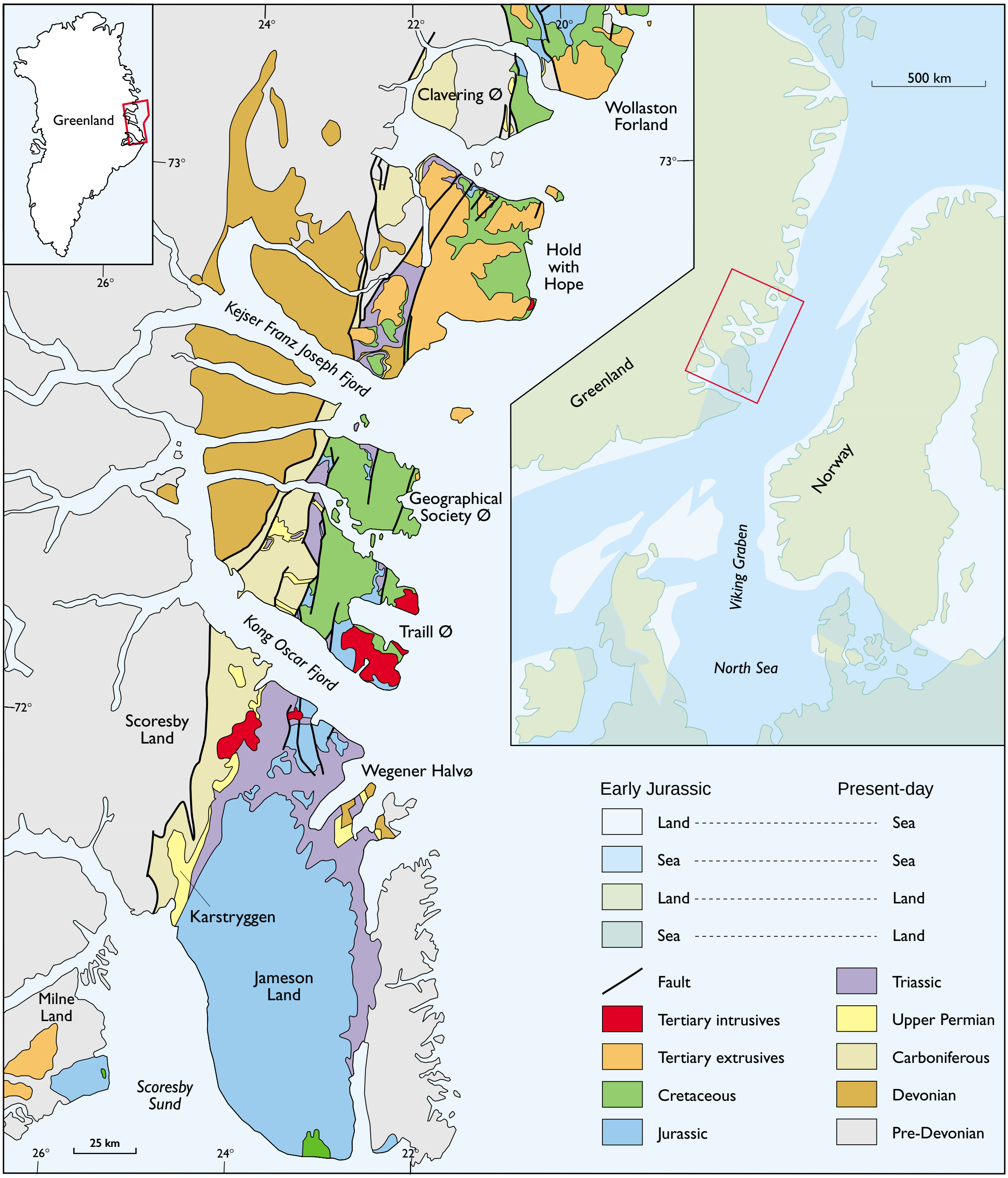

Fig. 1. The position of Greenland and Norway in an Early Jurassic pre-drift reconstruction with a simplified geological map of East Greenland showing Upper Palaeozoic to Mesozoic sediments and Tertiary igneous rocks. Geological map modified from Stemmerik *et al.* (1997); pre-drift position from Dam & Surlyk (1995).

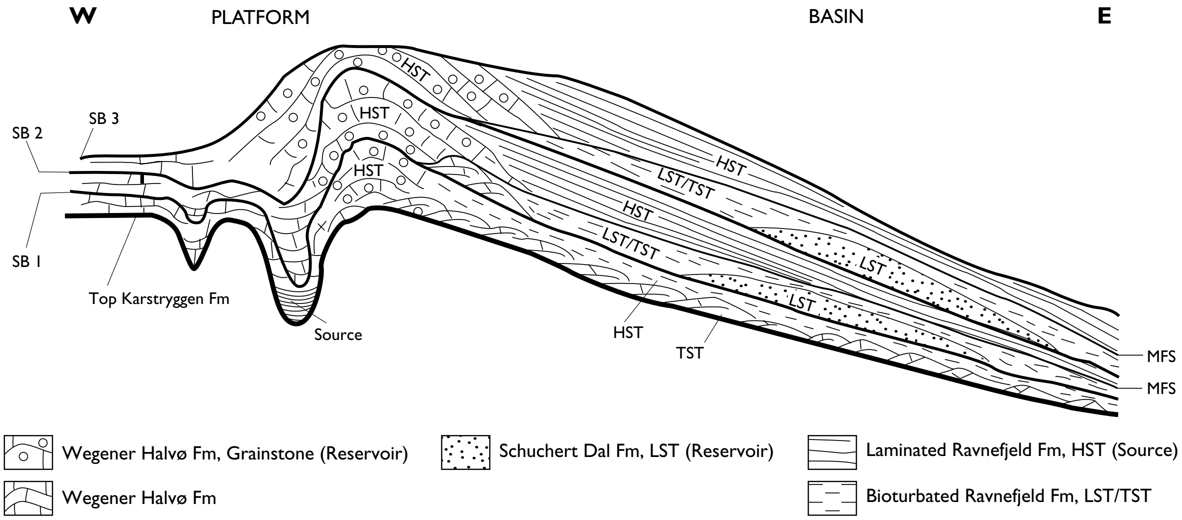

Fig. 2. Sequence stratigraphic model of the Upper Permian Wegener Halvø, Ravnefjeld and Schuchert Dal Formations in Jameson Land. Potential source and reservoir rocks are indicated. SB: sequence boundary; MFS: maximum flooding surface; LST, TST and HST: lowstand, transgressive and highstand systems tracts.

of well-exposed sedimentary basins can be used for more confident predictions of deeply buried potential source and reservoir rocks, and their spatial distribution in offshore basins with limited data sets. The most important implications are the genetic links between sea-level changes and the spatial distribution of sand depocentres and organic-rich, source-prone shales (e.g. in the Kap Stewart Group and the Hareelv Formation in East Greenland). Generalised models thus predict seaward displacement of sand depocentres during falling sea-level and deposition of sand-prone facies in basinal settings during sea-level lowstands. The best quality source rocks are predicted to occur during rising sea-level particularly during time intervals of high global sea-level. In the Jameson Land Basin, the sea-level control of source and reservoir rock distribution and quality can be studied in detail in well exposed and well dated successions of Late Permian and latest Triassic – Jurassic age.

The Upper Permian Foldvik Creek Group provides an example of a semi-arid carbonate-dominated depositional system where organic-rich, basinal shales were deposited during transgressions and early highstands and potential carbonate reservoir rocks formed along the margins of the surrounding carbonate platforms. The Rhaetian–Sinemurian lacustrine Kap Stewart Group consists of organic-rich shales deposited during lake-level rise and highstand alternating with sandy reservoir rocks formed during lake-level fall and lowstand. The overlying Pliensbachian–Volgian succession provides examples of marine siliciclastic systems with multiple reservoir rocks. Deposition of potential source rocks for oil mainly occurred during pronounced transgressive phases in the Aalenian and the Late Oxfordian – Kimmeridgian.

Upper Permian: Wegener Halvø and Ravnefjeld Formations

Sediments included in the Upper Permian Foldvik Creek Group are subdivided into two low order sequences and at least six higher order sequences. The basin fill outlines a temporal development from a shallow marine, evaporitic basin to a normal marine carbonate-dominated system with a deep central shale basin. Eventually the carbonate system was completely drowned and the final basinal fill is composed of deep-water turbidites and shales (Surlyk *et al.* 1986a,b; Kreiner-Møller 1998).

The present study focuses on the upper, normal marine part of the Foldvik Creek Group corresponding to the Wegener Halvø and Ravnefjeld Formations when the basin was divided into shallow water carbonate platforms and a deep marine, central shale basin (Fig. 2; Surlyk *et al.* 1984, 1986a; Piasecki & Stemmerik 1991; Christiansen *et al.* 1993; Stemmerik *et al.* 1993). Extensive organic-rich shales of the Ravnefjeld Formation with source potential for petroleum were deposited in the central parts of the basin. New data from cores drilled in a back-barrier position on the Karstryggen carbonate platform show that organic-rich shales were also deposited in intraplatform lows (L. Stemmerik, unpublished data 1998). Reservoir rocks are mainly confined to shallow carbonate grainstones and build-ups located along the margins of the platform. Lowstand sandy turbidites occurring in a basinal position may represent an additional hitherto unrecognised type of reservoir (Stemmerik *et al.* 1997).

Three long-term sea-level cycles with a duration of about 1 Ma each are suggested to have occurred during the time interval of the Wegener Halvø – Ravnefjeld Formations. In the basinal areas the sea-level fluctuations led to deposition of interbedded organic-lean, bioturbated shales and organic-rich, laminated shales. The laminated shales are interpreted as having been deposited during sea-level rise and early highstand when siliciclastic material was sequestered in basin margin areas. The organic-rich intervals thin towards basin margins and the interbedded bioturbated shales grade into turbiditic sandstones representing lowstand fans. Deposition of shallow-water carbonates in platform areas was restricted to times of sea-level rise and highstand whereas the platforms were subaerially exposed during lowstand (Scholle *et al.* 1993). Well developed build- ups and grainstones are restricted to the uppermost high order sequence in the Wegener Halvø Formation where carbonate production was able to keep pace with the sea-level fluctuations (L. Stemmerik, unpublished data).

The sequence stratigraphic interpretation of the upper Foldvik Creek Group predicts that organic-rich shales are expected to have been deposited not only throughout the Jameson Land Basin but also in other onshore and offshore basins in the rifted seaway between Greenland and Norway. The thickness and quality of the source rock units are uniform in most areas, although the shales formed during the latest sea-level cycle show some thinning and dilution towards platform margins. The source-prone units are much thinner and of sub-economic interest in sand-dominated lowstand fan areas.

Deposition and diagenesis of potential carbonate reservoir rocks are closely related to sea-level fluctuations. Deposition took place during rising and high relative sea-level when the platforms were flooded, whereas carbonate porosity was enhanced and preserved during periods of subaerial exposure and dissolution. This type of reservoir is therefore confined to up-dip areas that were subaerially exposed during lowstand. Localised carbonate lowstand reservoirs composed of resedimented, poor reservoir quality carbonates off carbonate platforms, are predicted to occur in basinal areas, whereas good quality siliciclastic sandstone reservoirs are predicted to occur in areas with poorly developed carbonate platforms marking entry points of rivers and deltas.

Uppermost Triassic – lower Middle Jurassic: Kap Stewart and Neill Klinter Groups

Sediments included in the Rhaetian–Sinemurian Kap Stewart Group and the Pliensbachian–Aalenian Neill Klinter Group were deposited in a basin open to the south and closed to the west, east and north (Dam & Surlyk 1993, 1995, 1998). The Kap Stewart Group was deposited in an extensive lake which alternated between hydrologically closed and open states. Along the margins, alluvial-plain, delta-plain and delta-front environments dominated whereas lacustrine conditions characterised the central part of the basin.

Depositional patterns changed in the Pliensbachian when the basin underwent marine transgression. During the early stages of deposition of the Neill Klinter Group, the area formed a shallow marine embayment dominated by shoreface, tidal channel, subtidal shoal and offshore transition deposits (Fig. 3). In Aalenian – Early Bajocian times a sea-level rise resulted in deposition of restricted shelf mudstones of the Sortehat Formation throughout the basin.

Organic-rich shales with source potential are well documented both from the open-lacustrine shale succession of the Kap Stewart Group (Dam & Christiansen 1990; Krabbe 1996) and the basal, transgressive part of the Sortehat Formation (Krabbe *et al.* 1994; Krabbe 1996), whereas thick sandstones are present in both the fluvial-lacustrine Kap Stewart Group and the shallow marine Neill Klinter Group along the eastern, western and northern basin margins.

High-resolution sequence stratigraphic analysis of the lacustrine Kap Stewart Group indicates that deposition took place in response to two orders of lake-level variations. The lake was low-lying and marine areas were located nearby in the seaway between Greenland and Norway. Long term cyclicity in lake level was possibly controlled by fluctuations in sea-level whereas high frequency fluctuations were more likely controlled by Milankovitch-type climate cycles (Dam & Surlyk 1993). Repeated climatically controlled lake-level falls and associated forced regressions resulted in deposition of sheet deltaic sandstones towards the basin centre whereas dark organic-rich lacustrine shales were deposited during periods of rise and highstand.

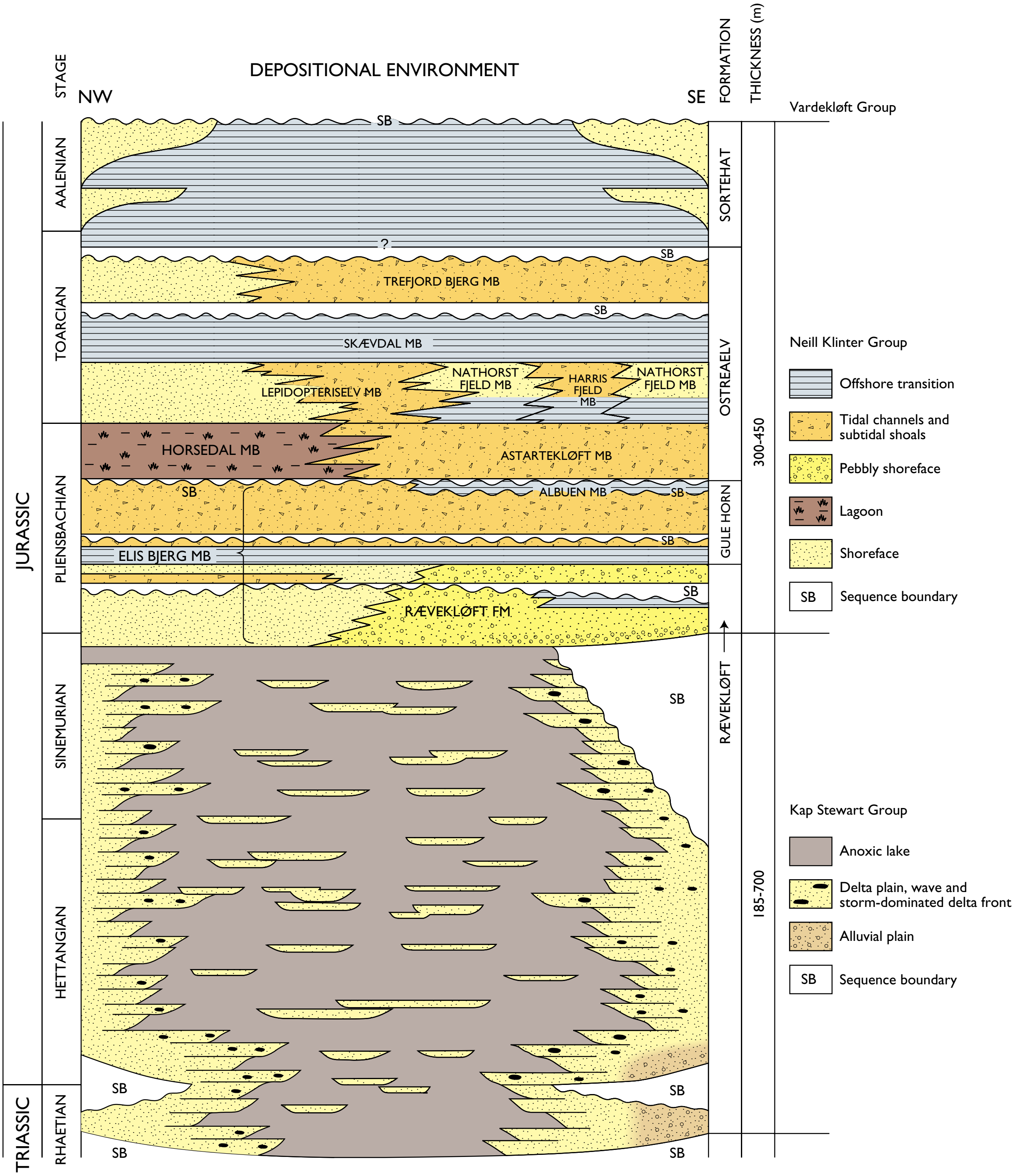

Fig. 3. Sequence stratigraphic scheme of Kap Stewart and Neill Klinter Groups. Slightly modified from Dam & Surlyk (1998, fig.3).

The Neill Klinter Group is subdivided into seven sequences, each with an overall sheet geometry and a duration of 1–2 Ma (Fig. 3; Dam & Surlyk 1995, 1998). Most sequences are characterised by near absence of well-defined parasequences, which is interpreted as reflecting a high rate of influx of sand. Continuous filling of accommodation space and erosion led to poor development of facies cyclicity and to amalgamation of parasequences. A direct correlation of systems tracts on a scale of a few tens of metres between East Greenland and the mid-Norwegian shelf seems to be possible (Dam & Surlyk 1995) and the Neill Klinter Group sequences are being used by several major oil companies as direct analogues to major Norwegian oil fields.

Sequence stratigraphic analysis of the Kap Stewart Group predicts a thick shale-dominated unit of interbedded organic-rich and organic-lean units to be present in the central part of Jameson Land. High frequency lake-level fluctuations controlled the organic content of the shales and the source-prone intervals are suggested to have formed during high lake-level stand (Dam & Christiansen 1990). The low order lake-level falls caused progradation of alluvial and deltaic sediments and the model predicts thick lowstand fan deposits to be present in the buried central parts of the lacustrine basin. Thinner lowstand deltaic sandstones are associated with high frequency, lake-level falls.

Sequence stratigraphic analysis of the overlying Neill Klinter Group constrains the lateral distribution and internal architecture of four major potential reservoir units. They occur in the upper Elis Bjerg Member, the Astartekløft Member, the Nathorst Fjeld, Harris Fjeld and Lepidopteriselv Members, and the Trefjord Bjerg Member (Fig. 3). Organic-rich shales with source rock potential are not associated with the reservoir units but are confined to the overlying Sortehat Formation deposited during the Aalenian – Early Bajocian sea-level rise.

The dominant depositional motif of the Elis Bjerg Member is aggradational to progradational stacking of amalgamated tidal channel and subtidal shoal facies packages of the transgressive systems tract followed by the highstand systems tract. Deposition took place during conditions of high sediment influx into a flat-bottomed basin with a moderate rate of creation of new accommodation space. The highstand systems tract is characterised by the development of major tidal channel complexes, forming some of the best potential hydrocarbon reservoirs in the Neill Klinter Group. The Elis Bjerg Member is capped by offshore transition zone mudstones of the subsequent transgressive systems tract.

The base of the Astartekløft Member is a major unconformity marking the incoming of subtidal shoal and tidal channel deposits corresponding to a marked seaward shift in facies. The deposits are interpreted as a thickly developed lowstand systems tract and constitute a major reservoir unit in the south-eastern part of the basin.

The overlying Nathorst Fjeld and Harris Fjeld Members consist of a single coarsening-upward unit composed of offshore transition zone mudstones grading upward into shoreface sandstones. The Nathorst Fjeld Member interfingers with seaward-prograding low-angle clinoform-bedded ebb-tidal delta deposits of the Harris Fjeld Member and is referred to the transgressive systems tract. Towards the north, the deposits of the Nathorst Fjeld and Harris Fjeld Members pass into coarse-grained tidal channel and fine-grained shoreface deposits of the Lepidopteriselv Member (Fig. 3). The complex formed by the Nathorst Fjeld, Harris Fjeld and Lepidopteriselv Members is capped by offshore transition zone mudstones of the Skævdal Member. The Skævdal Member shows a slight coarsening-upward trend grading into shoreface deposits and is interpreted as highstand deposits.

The Skævdal Member is truncated by a prominent basin-wide erosional unconformity draped by a lag conglomerate. The unconformity marks a basin-wide seaward shift in facies and is interpreted as a sequence boundary. It is overlain by coarse-grained tidal channel and subtidal shoal and shoreface sandstones of the Trefjord Bjerg Member, interpreted as a transgressive systems tract (Dam & Surlyk 1995, 1998). The sandstones of the Trefjord Bjerg Member are capped by offshore mudstones of the Sortehat Formation.

At several localities, the sandstones of the Trefjord Member and the mudstones of the Sortehat Formation are separated by a pebble strewn drowning surface. This surface has, on the basis of field appearance, macrofossil content, organic geochemistry and the palynological assemblages been interpreted as a coalesced sequence boundary and transgressive surface (cf. Dam & Surlyk 1998).

Middle–Upper Jurassic

The Middle–Upper Jurassic deposits of the Jameson Land Basin have served for many years as an excellent analogue model for the petroliferous strata of the northern North Sea and mid-Norwegian shelf. The succession forms a long-term overall transgressive-regressive cycle that was initiated with maximum regression in the

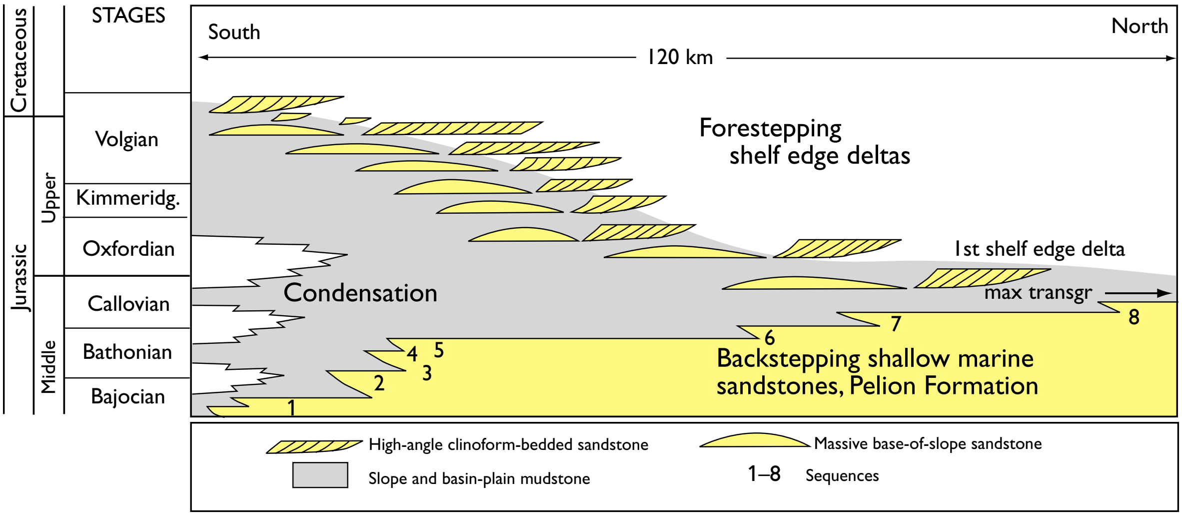

Fig. 4. Sequence stratigraphical model of the Middle and Upper Jurassic succession in Jameson Land. Numbers 1 to 8 mark eight composite third order sequences (VK 1–8) in the Pelion and Fossilbjerget Formations. The forestepping system of shelf edge deltas, base-of-slope sandstones and basinal mud refers to the Hareelv, Olympen and Raukelv (including the Sjællandselv Member) Formations.

early Late Bajocian, had a first transgressive maximum in the Middle Callovian, an Oxfordian regressive interlude, maximum transgression and turn around point in the Early Kimmeridgian and maximum regression in the latest Volgian. The duration of the complete long term transgressive-regressive cycle is 31 Ma. The Late Bajocian – Early Callovian transgressive portion of the cycle lasted for 11–12 Ma, the Oxfordian regressive pulse had a duration of 8 Ma, and the upper regressive part of 19–20 Ma (time scale after Gradstein *et al.* 1995).

Upper Bajocian – Middle Callovian: Pelion and Fossilbjerget Formations

The lower boundary of the sandy Pelion Formation is a regional unconformity. It marks a major reorganisation of the drainage system and the depositional basin, reflecting initiation of the main Mesozoic rift phase in the North European – North Atlantic region. Onset of marine sand deposition is essentially isochronous throughout Jameson Land, Traill Ø and Geographical Society Ø (Upper Bajocian *borealis* Chronozone). The upper boundary of the Pelion Formation is highly diachronous and youngs in a south–north direction from the Upper Bajocian to the Lower Callovian. The Late Bathonian – Early Callovian time interval was characterised by the influx of enormous amounts of relatively well-sorted, medium-grained quartzose sands deposited in a major deltaic system that was reworked by marine processes, notably tides and waves. The deltaic succession has the same overall style and architecture as the contemporaneous delta systems of the Brent Group and the Fangst Group which constitute the main reservoir units in the Viking Graben of the northern North Sea and mid-Norwegian shelf, respectively. The sandy Pelion Formation delta prograded southward along the basin axis. The basin axis had a very low inclination, and deposition was sensitive to even small changes in relative sea-level. Minor, high order sea-level changes with a duration of a few hundred thousand years caused the shorelines to advance or retreat in a north–south direction over tens to several hundred kilometres. The formation consists almost exclusively of marine sandstones deposited in shoreface, transition zone and offshore environments (Heinberg & Birkelund 1984; Engkilde & Surlyk in press).

The Pelion Formation and the correlative offshore Fossilbjerget Formation comprise a total of 28 high order sequences, with an average duration of about 360 Ka (Engkilde 1994; Engkilde & Surlyk in press). They can be grouped into eight composite third order sequences termed VK 1–8 with an average duration of 1–2 Ma. The stacked third order sequences form the lower transgressive part of the long-term Middle–Late Jurassic transgressive-regressive cycle (Fig. 4).

The Upper Bajocian sequences VK 1–2 include the most basinally positioned shallow marine sandstones, deposited during major sea-level lowstands. Lowstand deposition was separated by significant marine flooding events during which the area of sand deposition shifted far northward up the rift axis. The uppermost Bajocian – Middle Bathonian sequences VK 2–4 show an overall aggradational stacking pattern. The base of VK 5 coincides with the top of the Pelion Formation in south central Jameson Land and marks a major shift from shoreface to offshore environments. Large-scale backstepping took place during deposition of the Upper Bathonian – Middle Callovian sequences VK 5–8, and was followed by maximum transgression in the Late Callovian during which the marine-reworked delta of the Pelion Formation was finally drowned (Fig. 4). Distally, in southern Jameson Land this level is represented by a highly condensed unit spanning the uppermost Bathonian – Middle Oxfordian interval.

The backstepping clastic wedge of the Upper Bajocian – Middle Callovian Pelion Formation is composed of clean, well sorted quartzose sandstones. Pebbly sandstones occur at some levels, whereas mudstones are virtually absent. There are thus no significant permeability barriers within the formation but many flooding surfaces have been lithified by early carbonate cement and these horizons may exert some control on vertical fluid flow (Engkilde 1994). The sequences are dominated by coarsening-upward sandstone units, normally 0.3 m to tens of metres thick, which show high, slightly upwards-increasing porosity and permeability values and excellent reservoir quality. The distal thickness of the Pelion Formation sandstones is about 10 m, increasing gradually northward over a distance of more than 200 km to a thickness of the order of 600 m. The formation thus constitutes a huge potential reservoir body with extremely uniform facies. It is overlain by, and passes southwards into, the micaceous silty mudstones of the Fossilbjerget Formation.

Upper Callovian – Middle Oxfordian: Olympen Formation

Drowning of the Pelion Formation delta was completed by the Late Callovian coinciding with a change of the depositional system from transgressive to regressive (Fig. 4). The Late Jurassic time interval was characterised by marked progradation punctuated by a major Kimmeridgian transgression and subsequent minor flooding events. By the end of the Jurassic period, progradation of shallow marine sandstones had reached southernmost Jameson Land. The north–south distance of Late Jurassic progradation amounts to more than 200 km.

The Upper Callovian – Middle Oxfordian Olympen Formation represents the first regressive deposits after the Late Callovian maximum flooding of the basin. The formation was deposited during two southward progradational phases separated by a major drowning event in the Early Oxfordian (Larsen & Surlyk in press). The first phase was marked by the incoming of massive mass-flow slope and base-of-slope sandstones, but the delta front and top did not reach the area of present exposure. The second phase was initiated with a thick slightly progradational mudstone succession indicating that the deltaic deposition had shifted far to the north during the drowning event. Southward progradation of the delta was heralded by the incoming of massive base-of-slope sandstones, and this time the cross-bedded and clinoform bedded sandstones of the delta front and delta top reached the area.

The mudstones of the top of the underlying Fossilbjerget Formation and the lower massive sandstone unit of the Olympen Formation form an undifferentiated highstand – falling stage – lowstand systems tract. The top of the sandstone represents the basinal correlative of the transgressive systems tract and an organic-rich level in the overlying mudstones represents the maximum flooding zone. The remainder of the mudstone unit and the overlying massive sandstones of the second progradational phase form the highstand systems tract. The succeeding cross-bedded delta front sandstones are placed in the falling stage systems tract and their sharp base is interpreted as a marine regressive surface of erosion. The sharp base of the overlying clinoform bedded sandstones is a sequence boundary and these sandstones are referred to the lowstand systems tract.

The Olympen Formation provides an interesting analogue for important Upper Jurassic oil and gas reservoirs of the mid-Norwegian shelf, especially the giant Troll gas field.

Upper Oxfordian – Volgian: Hareelv Formation

Subsequent Late Jurassic progradation is only represented by slope and base-of-slope deposits of the Hareelv Formation which forms the youngest preserved unit in much of southern Jameson Land (Surlyk 1987). It consists of black organic-rich mudstones with thick, highly irregular, lenticular bodies of massive, well-sorted sandstones. The Upper Oxfordian part of the formation has roughly equal proportions of sandstone and mudstone whereas the Kimmeridgian–Volgian Sjællandselv

Member, has a very low content of mudstones and is dominated by thick massive sandstones.

The mudstones were deposited from suspension in poorly oxygenated slope and basinal environments. The content of organic carbon varies from 1–13% but the Hydrogen Index is less than 350 due to dominantly type II kerogen.

The sandstones were deposited in slope and base-of-slope gullies from sandy debris flows and erosive, high-density turbidity currents. They do not show any vertical or lateral trends in thickness and stacking pattern and form a completely disorganised sedimentary system. The sands were liquefacted subsequent to deposition. Major overhanging load structures were developed along the margins of the sand bodies, and sand was intruded as dykes and sills into the surrounding mudstones. The timing of liquefaction is difficult to estimate. There is evidence for some penecontemporaneous liquefaction and intrusion. Most of the soft sediment deformation seems, however, to have taken place after burial by a relatively thick cover of mudstone. The mudstones were mainly compacted at the time of sand intrusion as indicated by the angular shapes of mudstone clasts or rafts, the sharp boundaries of sandstone dykes and sills, and lack of mixing between mudstone and sandstone. The top of the sandstone bodies is very irregular and commonly shows onion-shaped mounds with abundant soft-sediment flow moulds on the surface. This indicates liquefaction and intrusion of the whole sand body after burial under as much as several tens of metres. The intrusive sandstone bodies provide a unique analogue model for enigmatic Paleogene reservoir bodies in the North Sea (cf. Dixon *et al.* 1995).

The dominance of sandstone in the upper part of the Hareelv Formation reflects an increase in eustatic fall at the end of the Jurassic period and associated long-distance southwards progradation to the shelf edge. The Sjællandselv Member thus represents an extremely sand-rich slope and base-of-slope reservoir of mass-flow origin which passes up-dip into cross-bedded sandstones representing shelf-edge deltas.

Volgian: Raukelv Formation

Progradation of shelf-edge deltas reached southernmost Jameson Land in the Volgian (Surlyk & Noe-Nygaard 1991, 1995, 1998; Surlyk *et al.* 1993). A succession of at least five, up to 50 m thick, high-angle clinoform-bedded sandstone sheets makes up the Raukelv Formation, and represents a forestepping set of shelf edge deltas. They prograded eastwards to the outermost shelf and shelf-edge areas during sea-level fall and lowstand. There is abundant evidence for tidal activity in the sand bodies; they were not directly attached to a river mouth but were reworked by marine longshore tidal and storm-induced currents.

The high-angle, clinoform-bedded, marine reworked shelf-edge deltas wedge out gradually towards the western basin margin where they are represented by a major hiatus. They are topped by pebble lags and are separated by glauconitic transgressive sandstones.

In some exposures, the transition from the delta front to slope and base-of-slope can be directly observed. When the delta reached the shelf-edge, progradation continued over the upper slope, the delta front started to collapse and mass flows were triggered down the slope. The upper slope thus shows a range of transitions from cross-bedded to massive sandstones separated by scours and slide planes. In the lower slope, base-of-slope and proximal basin, only massive mass flow sandstones were deposited. The proportion of mudstone increases gradually southwards in the axial direction from close to zero in the slope area up to 100% in the most distal exposed part of the basin.

The forestepping stack of marine-reworked shelf-edge delta sand bodies shows a clear time trend towards coarser grain-sizes, more basinal position and increased fluvial influence. This culminated with the development of a marked red-stained pebble strewn erosional surface at the top of the youngest delta. A large valley was incised in the edge and upper slope of the delta and a system of fluvial tributary channels leading towards the valley margins was developed. The valley was probably formed by fluvial incision of the shelf edge enlarged by retrogressive slumping and marine erosion during succeeding transgression. The valley was filled by onlapping mudstones which towards the top coarsen upwards into fossiliferous sandstones which form the top of the valley fill. The unconformity at the top of the Raukelv Formation and the associated incised valley mark the end of the long-term Middle–Late Jurassic transgressive-regressive cycle.

The high-angle clinoform bedded sandstone packages of the Raukelv Formation form an excellent analogue for several important hydrocarbon reservoirs in the northern North Sea. Furthermore, the formation is a rare exposure of a complete shelf, shelf edge, slope, base-of-slope and proximal basin. It provides a highly illustrative example of shelf-edge delta progradation, delta front collapse, mass flow initiation and deposition.

Conclusions

High resolution sequence stratigraphic analysis of Permian and uppermost Triassic – Jurassic successions in Jameson Land, East Greenland provides new knowledge and a much better understanding of the importance of relative sea-level changes, tectonism and basin physiography for the development and distribution of potential source and reservoir rocks.

1. It is demonstrated that deposition of the oil-prone Upper Permian Ravnefjeld Formation extended to intraplatform lows during highstand, and that lowstand sandy turbidites represent an additional potential reservoir type (Fig. 2).

   High-resolution sequence stratigraphic analysis of the Rhaetian–Aalenian succession (Fig. 3) suggests the possibility of long-distance correlation at a systems tract level, on a scale of a few tens of metres, between East Greenland and the mid-Norwegian shelf across the present North Atlantic Ocean.

   The Middle and Upper Jurassic succession was deposited during an overall long-term transgressive-regressive cycle from the Late Bajocian to the latest Volgian with a first major flooding in the Early Callovian, and a second in the Early Kimmeridgian. The Pelion and Fossilbjerget Formations were deposited in a shallow marine basin with very low inclination of the basin axis and with rapid shoreline migration over tens to several hundred kilometres in a north–south direction. The overlying Olympen, Hareelv and Raukelv Formations were deposited in a deep marine basin with a steep basin axis. The significantly variable sand to shale ratio in the formations mainly reflects present-day preservation of shelf edge delta, slope and base-of-slope deposition during overall Late Jurassic regression (Fig. 4).

2. Four major potential source rocks for oil are identified in the Permian and Jurassic successions of the Jameson Land Basin and multiple clastic or carbonate potential reservoir rocks occur throughout the same succession. Sequence stratigraphic analysis of the succession shows that the spatial distribution and the formation of the potential source and reservoir rocks are closely linked to relative sea and lake-level variations.

   Fine-grained, organic-rich sediments were deposited in distal settings of transgressive and highstand systems tracts at many levels in the studied succession, but became oil-prone only when deposited in low oxygen environments, e.g. in the Ravnefjeld Formation (marine), the Kap Stewart Formation shales (lacustrine), the lower Sortehat Formation (marine, brackish) and the Hareelv Formation (marine).

   Based on sequence stratigraphic models it is predicted that correlative sedimentary units with source potential occur not only in East Greenland but also in other basins of the North Atlantic region. This applies to the marine Ravnefjeld Formation and the marine–brackish Sortehat Formation.

3. Carbonate reservoirs (Wegener Halvø Formation build-ups and platforms) associated with potential source rocks (Ravnefjeld Formation) were deposited during highstands but subaerial exposure during lowstands enhanced and preserved porosity.

   Clastic sedimentary units with reservoir potential directly associated with potential source rocks were formed both as lowstand fans (Schuchert Dal Formation), basinal forced regressive sheet sands deposited during repeated lake-level falls (Kap Stewart Group) and slope to base-of-slope gully sandstones slumped from lowstand shelf edge deltas (Hareelv Formation).

4. Most large oil and gas fields in the North Atlantic region have depositional analogues in the Jameson Land Basin, that may be used for comparative studies.

Acknowledgements

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Wandel Sea Basin, eastern North Greenland

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The Wandel Sea Basin in eastern North Greenland is the northernmost of a series of fault-bounded Late Palaeozoic – Early Tertiary basins exposed along the eastern and northern margin of Greenland (Fig. 1). The basin and the surrounding shelf areas are located in a geologically complex region at the junction between the N–S trending Caledonian fold belt in East Greenland and the E–W trending Ellesmerian fold belt in North

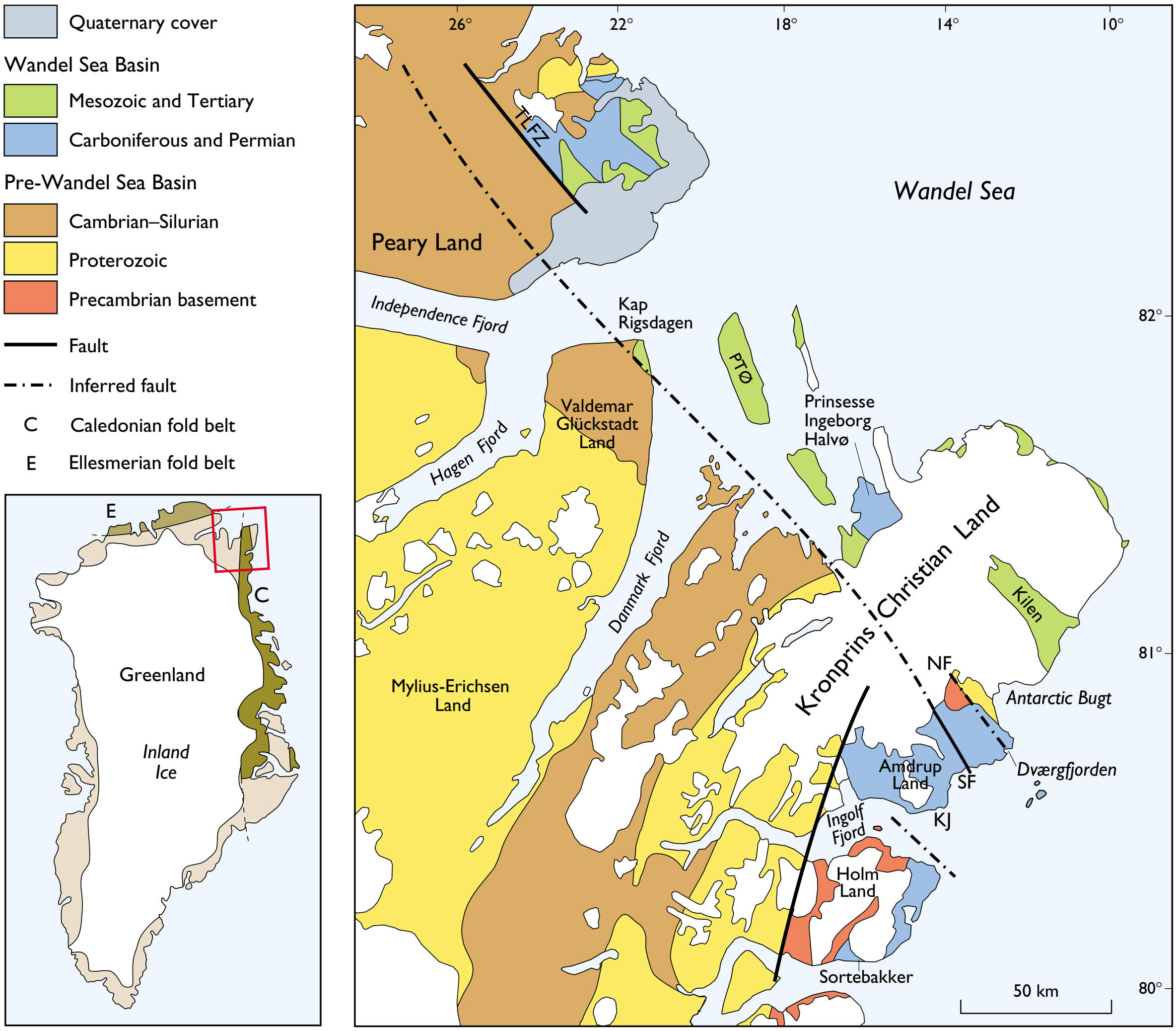

Fig. 1. Simplified geological map of the Wandel Sea Basin with locations mentioned in the text. SF: Sommerterasserne fault, NF: north Amdrup Land fault, PTØ: Prinsesse Thyra Ø, KJ: Kap Jungersen, TLFZ: Trolle Land fault zone. Modified from Stemmerik *et al.* (1994).

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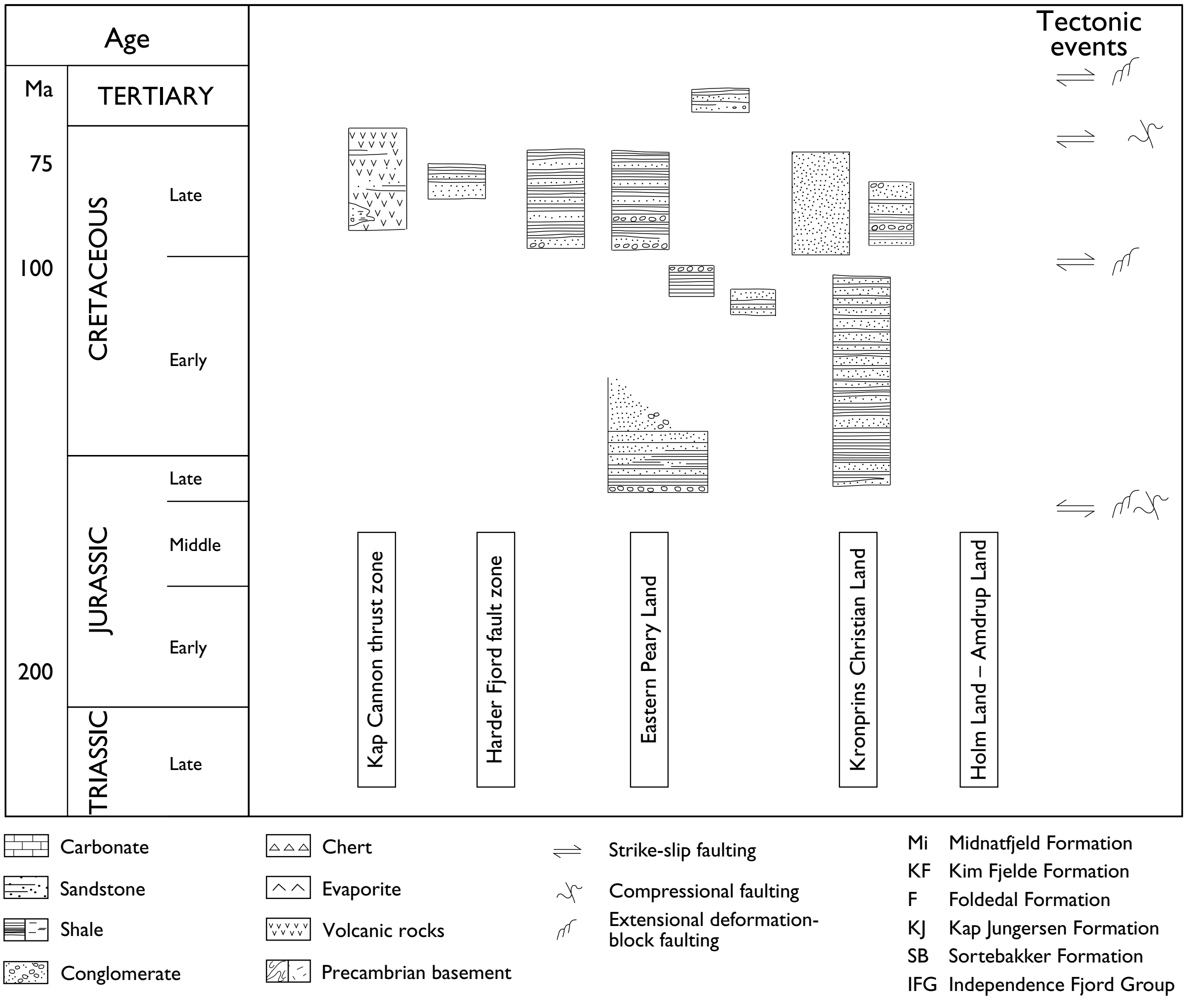


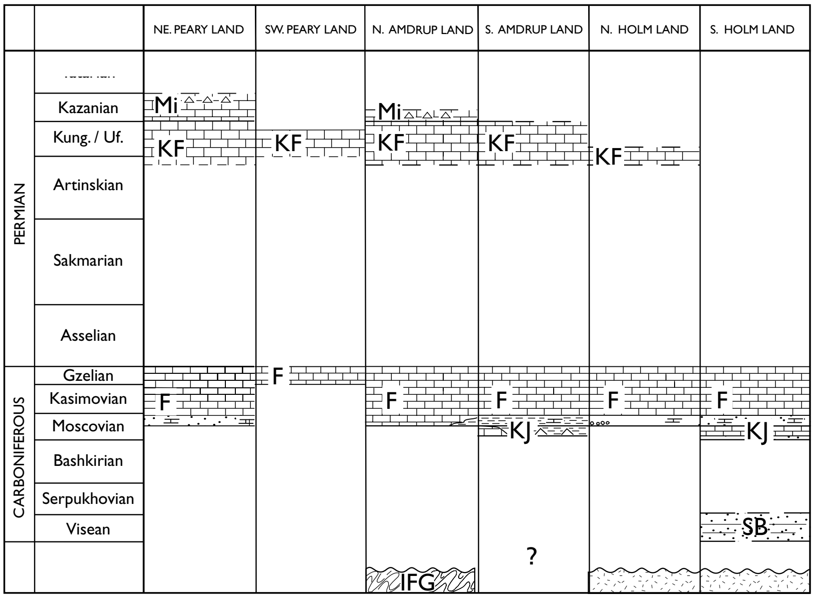


Fig. 2. Simplified stratigraphy of the Wandel Sea Basin. **Above**: Distribution of Mesozoic–Tertiary sediments in the northern part of the basin. **Below**: Scheme showing correlation of the Upper Palaeozoic deposits in the modelled areas.

Greenland, and along the zone of later, Tertiary, continental break-up. The Wandel Sea Basin started to develop during the Carboniferous as a result of extension and rifting between Greenland and Norway, and Greenland and Spitsbergen (Håkansson & Stemmerik 1989), and was an area of accumulation during the Early Carboniferous – Early Tertiary period. Two main epochs of basin evolution have been recognised during previous studies of the basin fill: an early (late Palaeozoic – early Triassic) epoch characterised by a fairly simple system of grabens and half-grabens, and a late (Mesozoic) epoch dominated by strike-slip movements (Håkansson & Stemmerik 1989). The Mesozoic epoch only influenced the northern part of the basin, north of the Trolle Land fault zone (Fig. 1). Thus the northern and southern parts of the basin have very different structural and depositional histories, and accordingly different thermal histories and hydrocarbon potential.

This paper summarises the results of a project supported by Energy Research Program (EFP-94), the purpose of which was to model the Wandel Sea Basin with special emphasis on hydrocarbon potential and late uplift history, and to provide biostratigraphic and sedimentological data that could improve correlation with Svalbard and the Barents Sea. It is mainly based on material collected during field work in Holm Land and Amdrup Land in the south-eastern part of the Wandel Sea Basin during 1993–1995 with additional data from eastern Peary Land (Stemmerik *et al.* 1996). Petroleum related field studies have concentrated on detailed sedimentological and biostratigraphic studies of the Carboniferous–Permian Sortebakker, Kap Jungersen, Foldedal and Kim Fjelde Formations in Holm Land and Amdrup Land (Fig. 2; Døssing 1995; Stemmerik 1996; Stemmerik *et al.* 1997). They were supplemented by a structural study of northern Amdrup Land in order to improve the understanding of the eastward extension of the Trolle Land fault system and possibly predict its influence in the shelf areas (Stemmerik *et al.* 1995a; Larsen 1996). Furthermore, samples for thermal maturity analysis and biostratigraphy were collected from the Mesozoic of Kap Rigsdagen and the Tertiary of Prinsesse Thyra Ø (Fig. 1).

Biostratigraphy and correlation

New biostratigraphic data were obtained from the Carboniferous–Permian, Jurassic and Tertiary intervals in the course of this project (Stemmerik *et al.* 1997; J.H. Callomon & I. Nilsson and S. Piasecki & J. Utting, unpublished data). These biostratigraphic data are important, not only as they form the basic framework for the basin modelling, but also because they allow correlation to the adjacent areas with greater confidence.

Early Carboniferous

The Lower Carboniferous Sortebakker Formation (Figs 2, 3) is the oldest unit of the Wandel Sea Basin. It rests directly on crystalline basement rocks affected by the Caledonian orogeny in southern Holm Land. The formation consists of more than 1000 m of fluvial deposits with a poorly preserved macroflora that suggests an Early Carboniferous age for the formation. During this study, a poorly preserved but stratigraphically confined microflora was found in the upper part of the formation (Stemmerik *et al.* 1997); the presence of *Tripartites distinctus, Raistrickia corynoges, Potoniespores delicatus* and *Savitrisporites nux* is indicative of the late Visean NM Zone of the West European system. This means that the upper part of the formation can be correlated with the Nordkapp Formation on Bjørnøya, the upper Billefjorden Group of Spitsbergen and the lower Traill Ø Group of East Greenland (Stemmerik *et al.* 1997). Sediments of this age also occur in the offshore areas of the Finnmark Platform in the southern Barents Sea (Bugge *et al.* 1995).

Late Carboniferous

The Carboniferous Kap Jungersen and Foldedal Formations show marked differences in depositional history and diagenesis between southern Amdrup Land, southern Holm Land and northern Amdrup Land. The succession in Holm Land consists of laterally widespread mixed siliciclastic-limestone cycles whereas at Kap Jungersen the succession consists of more laterally confined cycles that locally form large platforms (Stemmerik & Elvebakk 1994; Stemmerik 1996). The Kap Jungersen Formation is absent in northern Amdrup Land where the Carboniferous succession is much thinner and composed mainly of dolomitised limestones.

The Kap Jungersen Formation has been dated by fusulinids (Dunbar *et al.* 1962; Stemmerik & Håkansson 1989; Nilsson *et al.* 1991; Nilsson 1994; Stemmerik *et al.* 1996). Based on field work in 1993–1995, the zonation of the successions in Holm Land and Amdrup Land has been considerably refined, and it is now possible to correlate on fusulinid zone level both within the basin and with the Barents Sea succession. The oldest marine sediments in Holm Land and Amdrup Land include a fusulinid assemblage dominated by *Profusulinella* spp., *Pseudostaffella* spp., *Eofusulina* aff. *E. triangula* and ?*Aljutovella* sp.. This assemblage shows close similarities to the early Moscovian *Profusulinella* assemblage of Dunbar *et al.* (1962).

The overlying Foldedal Formation contains seven Late Carboniferous fusulinid assemblages. The lowest *Beedeina* fusulinid assemblage is characterised by *Beedeina* spp., *Wedekindellina* ex.gr. *uralica*, *Fusulinella* spp., *Neostaffella greenlandica, N. sphaeroidea* and *Taitzeoella* sp. and is considered to be of earliest late Moscovian age, whereas the *Fusulinella* ex.gr. *bocki* assemblage overlies sediments of latest Moscovian age. Next follow sediments with a *Protriticites–Quasifusulinoides* assemblage of possible latest Moscovian to earliest Kasimovian age. A distinct middle Kasimovian assemblage appears to be missing although *Montiparus* is recognised at one level at Antarctic Bugt; this genus first occurs in middle Kasimovian strata of the Russian Platform and disappears close to the base of the Gzelian. Upper Kasimovian strata are characterised by a *Rauserites* ex.gr. *simplex* assemblage with primitive *Rauserites* spp., *Schubertella* spp. and *Pseudofusulinella* spp. This fauna can be correlated with the *Rauserites* ex.gr. *simplex* assemblage of Nilsson (1994). The Gzelian succession can possibly be subdivided into three fusulinid assemblages. The presence of *Rauserites* aff. *R. rossicus* indicates an early to middle Gzelian age whereas a fauna with *Jigulites* sp., *Rauserites* spp. and primitive *Schellwienia* spp. is of possible middle Gzelian age. The youngest fusulinid fauna recorded in Holm Land and Amdrup Land comprises species of *Schellwienia* and ?*Daixinia* and may be of late Gzelian age.

Middle to Late Permian

Sediments belonging to the Upper Permian Midnatfjeld Formation were found to be widespread in a downfaulted area in northern Amdrup Land where they are conformably overlain by > 70 m of fine-grained sandstones and siltstones of Jurassic age (Stemmerik *et al.* 1994, 1995a, b). The Midnatfjeld Formation consists in this area of bioturbated chert-rich limestones and shales and thin, laterally widespread horizons of bioturbated chert, which conformably overlie older Permian limestones of the Kim Fjelde Formation. Middle to Late Permian sediments of the Kim Fjelde and Midnatfjeld Formations (Stemmerik *et al.* 1996) have mainly been dated by palynomorphs with additional information from conodonts, small foraminifers and brachiopods (Dunbar *et al.* 1962; Stemmerik & Håkansson 1989; Stemmerik *et al.* 1996). Based on palynomorphs, the Kim Fjelde Formation at Kap Jungersen is dated as Kungurian. The base of the Midnatfjeld Formation in northern Amdrup Land contains a microflora of Kazanian age (S. Piasecki & J. Utting, personal communication 1997).

Upper Jurassic

A > 70 m thick succession of post-Permian siliciclastic sediments are present locally in northern Amdrup Land. The sediments are preserved in the cores of synforms north of the Sommerterrasserne fault and provide a maximum age for the deformation in northern Amdrup Land. They have been dated as Oxfordian (Late Jurassic) by J.H. Callomon (personal communication 1996) on the basis of two ammonite fragments. The sequence can thus be correlated with the Ladegårdsåen Formation in eastern Peary Land and these sediments record a basin-wide onset of sedimentation following a mid-Triassic – mid-Jurassic hiatus.

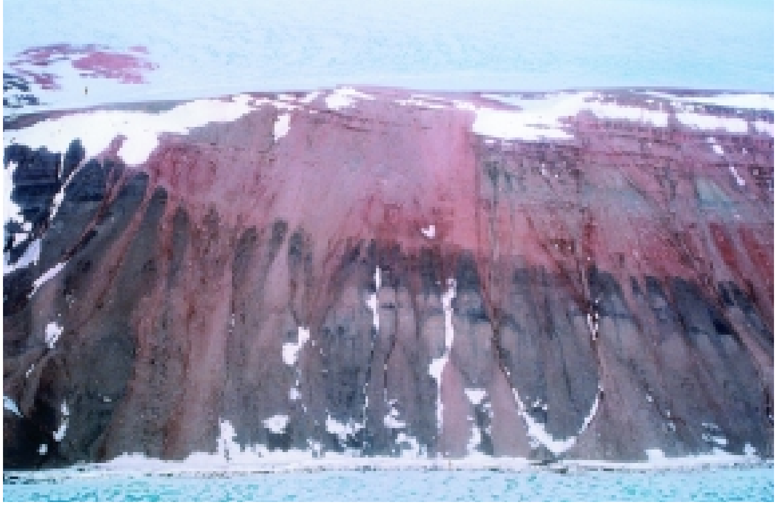
Tertiary

The Paleocene – ?Early Eocene Thyra Ø Formation forms the youngest preserved sediments within the Wandel Sea Basin and precise dating of these deposits is important for basin modelling. The formation was previously tentatively dated as Paleocene on the basis of the macroflora and rare dinoflagellates (Håkansson & Pedersen 1982; Håkansson *et al.* 1991). However, during this study a more diversified microflora containing both spores and pollen, and dinoflagellates was found (Stemmerik *et al.* 1997). The presence of *Cerodinium speciosum* and *Spinidinium pilatum* indicates a Paleocene age whereas *Cerodinium markovae* has a Paleocene–Eocene range and *Spinidinium sagittula* has been reported from sediments of Early Eocene age. Accordingly, the Thyra Ø Formation can be attributed a Late Paleocene to possibly Early Eocene age.

Structural geology

Structural studies of northern Amdrup Land show that the area north of the NW–SE trending Sommerterrasserne fault (Fig. 1) was affected by a compressional event in post-Jurassic time. In the graben area between the Sommerterrasserne fault and the north Amdrup Land fault the Permian and Jurassic strata are folded by gentle, *en echelon,* domal folds with amplitudes of approximately 100 m, wave lengths of 1–1.5 km and a lateral

Fig. 3. Unconformity between faulted fluvial sediments of the Lower Carboniferous Sortebakker Formation and mixed shelf siliciclastics and carbonates of the Upper Carboniferous Kap Jungersen Formation on the 450 m high Depotfjeld, southern Holm Land. Modelling shows that approximately 2000 m of Lower Carbonifeous sediments were removed prior to onset of deposition in the Late Carboniferous.



extent of 4–4.5 km. Fold axes generally strike NW–SE with some local variations. North of the northern Amdrup Land fault, Carboniferous sediments unconformably overlie Proterozoic sedimentary and volcanic rocks affected by Caledonian isoclinal folding. Here the Moscovian sediments are folded in somewhat larger domal folds with a NE–SW trend; a major synform with an amplitude of 250–300 m, a wave length of 3.5 km and a lateral extent of 7.3 km exposes Carboniferous, Permian and Jurassic sediments near Dværgfjorden (Larsen 1996).

The deformation of the Wandel Sea Basin deposits in Amdrup Land took place after deposition of the Upper Jurassic sediments, and should therefore be correlated with either the Middle Cretaceous Kilen event or the end of the Cretaceous strike-slip event of Pedersen (1988).

Basin modelling

Basin modelling of the Wandel Sea Basin is based on stratigraphic analysis of outcrop data and use of the Yükler 1D basin model concept (Mathiesen *et al.* 1997). The Yükler model is a forward deterministic model which quantifies the geological evolution of a sedimentary basin by calculating compaction, pressure, temperature, thermal maturity and hydrocarbon generation, as a function of time and space. Geological information and input data for the model include thickness, age, lithology, porosity, palaeotemperature, heat flow and palaeo-water depth. These data are synthesised into model events in such a way that the model can handle deposition, non-deposition (hiati) and erosion.

A total of 34 model events, each in excess of 1.0 Ma have been used to describe the evolution of the Wandel Sea Basin (Fig. 4). The lithology was based on published or unpublished sources on depositional facies variation. Data on thickness were taken from outcrop-based measurements (Håkansson 1979, 1994; Stemmerik & Håkansson 1989; Stemmerik *et al.* 1994, 1995b, 1996). The surface palaeotemperature was estimated from palaeoclimatic models and palaeolatitude. The variations in heat flow with time were estimated from the basin history, with higher values during periods of rifting and volcanic activity, and lower (and generally decreasing) values in tectonically stable periods with slow and uniform subsidence. The same heat flow history has been used for the whole area, except for a heating event around 65 Ma where the heat flow was increased to 1.35 heat flow units for the Peary Land and northern Amdrup Land area.

The model concept has been used to construct seven pseudowells in eastern Peary Land, Amdrup Land and Holm Land, in order to constrain basin history by optimising the subsidence, uplift and thermal history of the different parts of the basin using sensitive surface data (Mathiesen *et al.* 1997). Input data for each pseudowell are accumulated from a large area (often > 100 km^2), and the modelled pseudowells do not therefore correspond to real wells.

The seven pseudowells describe different geological scenarios within the basin. All pseudowells suggest limited Tertiary uplift of the onshore areas – in contrast to the Barents Shelf where more than 1 km of latest

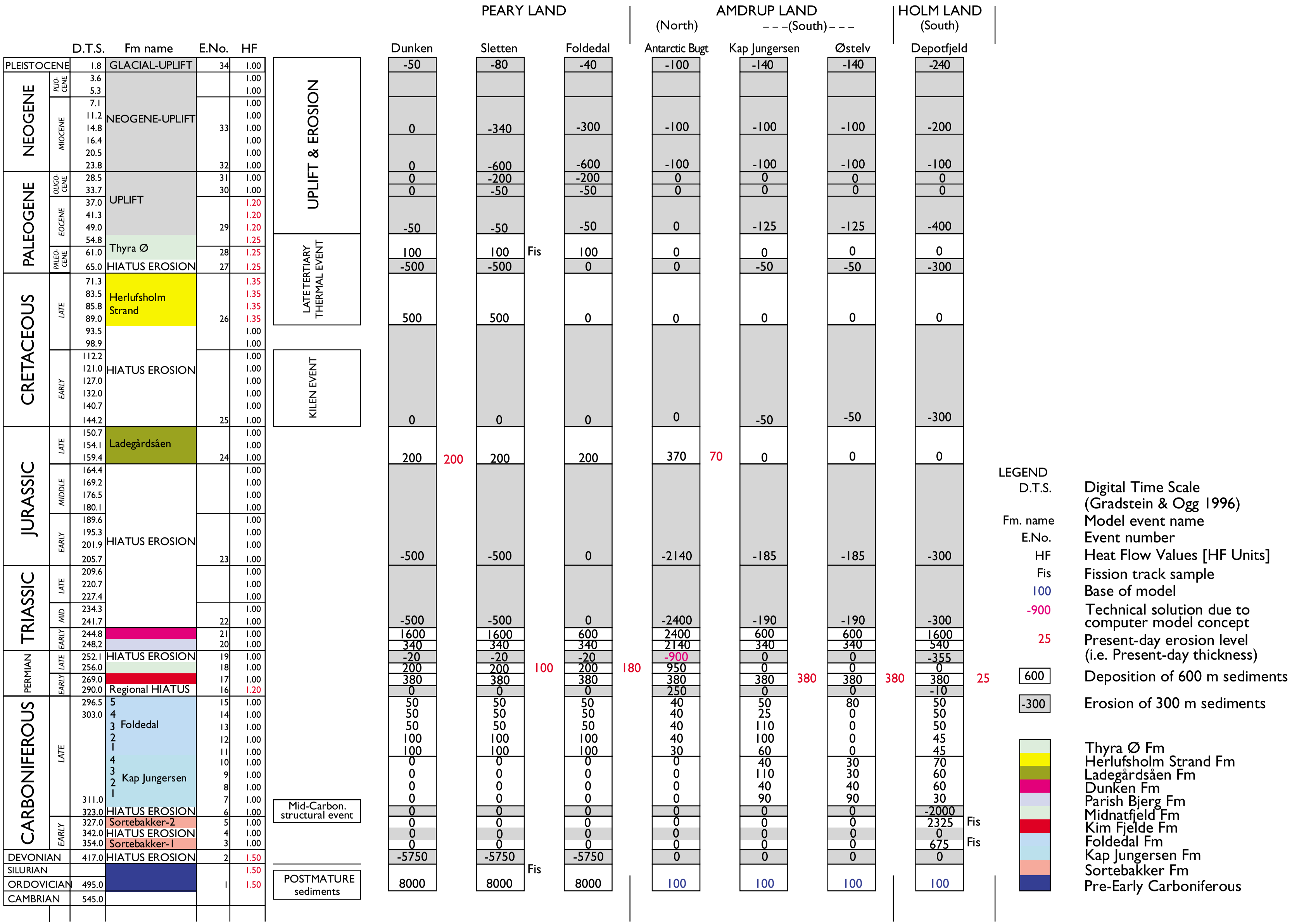


Fig. 4. Pseudowells in eastern Peary Land, Amdrup Land and Holm Land based on the basin modelling concepts applied to the Wandel Sea Basin by Mathiesen *et al.* (1997).

Tertiary to Recent uplift is proposed (Løseth *et al.* 1992). The Holm Land pseudowell puts constrains on the mid-Carboniferous structural event separating the Sortebakker and Kap Jungersen Formations (Figs 3, 4). According to the model at least 2000 m of Lower Carboniferous sediments have been removed during this event to explain the contrasting thermal maturity of the Lower and Upper Carboniferous sediments. Similarly, the Antarctic Bugt pseudowell shows that up to five kilometres of Upper Permian and Triassic sediments are likely to have been deposited in this area, and subsequently eroded away, to explain the contrasting thermal maturity of the Permian and Upper Jurassic sediments (Fig. 4).

Summary and conclusions

The results arising from the project form a major step forward in the understanding of the Wandel Sea Basin. The biostratigraphic resolution of the Upper Palaeozoic succession has been improved considerably and the basin modelling has provided the first quantitative constrains on the subsidence and uplift history of the basin. The most important new results are given below.

1. The finds of the first age diagnostic fossils from the Lower Carboniferous Sortebakker Formation which date the upper part of the formation as Visean.

2. Detailed sampling of fusulinids which allows recognition of eight Upper Carboniferous fusulinid assemblages and dating of all the main outcrops in Holm Land and Amdrup Land.

3. Discovery of new outcrops of Mesozoic sediments on Amdrup Land which have been dated as Late Jurassic based on ammonites.

4. Structural studies which show that the Trolle Land fault zone extends eastwards across northern Amdrup Land and also affected the northern part of the East Greenland Shelf.

In addition to the above observations basin modelling indicates that:

5. The mid-Carboniferous structural event separating the Sortebakker and Kap Jungersen Formations involved removal of at least 2000 m of Lower Carboniferous sediments before deposition of the Kap Jungersen Formation.

6. Up to 5 km of Upper Permian and Triassic sediments are likely to have been deposited in northern Amdrup Land, and subsequently eroded away, to explain the contrasting thermal maturity of the Permian and Upper Jurassic sediments.

7. Cretaceous sedimentation was very localised and no substantial post-Jurassic cover was present in Amdrup Land and the southern parts of eastern Peary Land.

8. Tertiary uplift of the basin was very limited.

The results imply that the shelf areas east of Holm Land and Amdrup Land have very different hydrocarbon potential. Immediately north of the Trolle Land fault zone it is suggested that mature Upper Palaeozoic sediments are folded in broad domal structures. Further to the north, the shelf area was most likely affected by a late Tertiary thermal event and the sediments are considered post-mature. South of the Trolle Land fault zone, the most prominent feature on the shelf is a north–south trending salt basin (Escher & Pulvertaft 1995). The outcrop studies and the basin modelling have only limited significance for evaluation of this area although sedimentological and diagenetic studies of the Upper Carboniferous carbonates may provide reservoir models for this region. Therefore the next phase of the investigation will focus on the relationships between Upper Carboniferous sedimentary facies and diagenesis, and the structural history of fault blocks. This study will compare the successions on southern Holm Land and southern Amdrup Land and will hopefully lead to a better understanding of the reservoir development in the offshore areas.

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Airborne geophysical surveys in central West Greenland and central East Greenland in 1997

Leif Thorning and Robert W. Stemp

In order to stimulate mining exploration activity in Greenland the Government of Greenland decided in 1993 to finance a five-year programme of airborne electromagnetic surveys over selected regions of Greenland, Project AEM Greenland 1994–1998. By the end of 1996 three surveys had been undertaken in various parts of Greenland (Stemp & Thorning 1995a, b; Stemp 1996a, b; Stemp 1997a, b). In 1992 the Danish Government financed a small aeromagnetic survey (Project Aeromag 1992; Thorning 1993). Regional aeromagnetic surveying was taken up again when the governments of Denmark and Greenland jointly financed two aeromagnetic surveys in 1995 and 1996 – the projects Aeromag 1995 and Aeromag 1996 (Thorning & Stemp 1997).

To this suite of airborne geophysical surveys of selected regions in Greenland were added two surveys in 1997, both financed by the Government of Greenland. The fourth year of Project AEM Greenland 1994–1998 encompassed a transient electromagnetic (GEOTEM) and magnetic survey over northern Jameson Land, central East Greenland, while Project Aeromag 97 added a regional aeromagnetic survey over Disko Bugt – Nuussuaq, central West Greenland. As in previous years, commercial geophysical contractors carried out the survey operations in Greenland according to an agreement with the Geological Survey of Denmark and Greenland (GEUS) entered into after international tendering following rules of the European Union. GEUS manages the projects and organises the distribution and use of the results. The new maps and digital data from the two 1997 surveys, a total of 85 252 line kilometres of data covering 51 414 km^2, were released to the public on 1 March 1998.

This note provides some introductory information about the two surveys. Further information can be found in reports by Stemp (1998) and Thorning (in press); both include a number of full-page colour anomaly maps from the survey areas.

The airborne geophysical programme will continue in 1998, and the areas to be surveyed have already been selected. The final year of Project AEM Greenland 1994–1998 will include combined GEOTEM and magnetic surveys over two regions in North Greenland: Washington Land in western North Greenland, where operations are expected to start in May 1998 operating out of Alert in Canada, and later in the season over J.C. Christensen Land in central North Greenland operating out of Station Nord in eastern North Greenland. Project Aeromag 1998 will continue the regional aeromagnetic survey programme in West Greenland, extending the coverage by including most of the region from 63°45′N to 66°N in southern West Greenland. This project will be based at Nuuk and start in March 1998. The Government of Greenland will finance all surveys in 1998.

Figure 1 shows all survey areas for the electromagnetic and magnetic surveys of Project AEM Greenland 1994–1998 and the aeromagnetic survey areas of Project Aeromag 1992, 1995, 1996, 1997 and 1998.

Project Aeromag 1997: central West Greenland

The regional aeromagnetic survey over the Disko–Nuussuaq region of central West Greenland (Fig. 1) includes onshore and offshore areas where there is ongoing exploration for both minerals and oil. While previous Aeromag surveys in 1992, 1995 and 1996 mainly covered onshore areas of interest for mineral exploration, the results obtained in 1997 will also be of major interest to petroleum exploration activities in the area.

Sander Geophysics Ltd. of Ottawa, Canada, carried out the survey operations. A total of 70 630 line km of high-resolution aeromagnetic data were acquired. The easternmost part of the survey area, mainly onshore Precambrian terrain, was flown with a line spacing of 500 m, while the westernmost part of the survey area, including off-

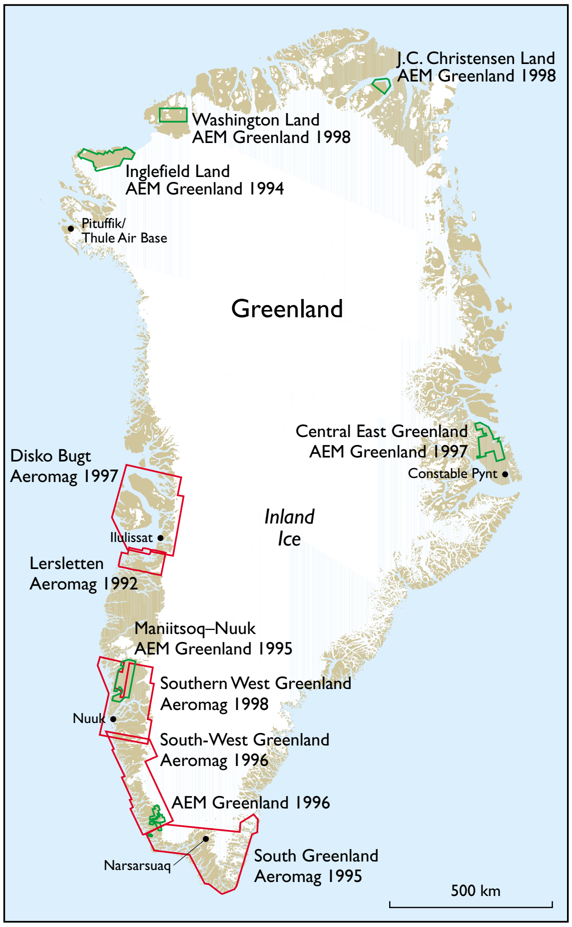

Fig. 1. Airborne geophysical surveys financed by the governments of Denmark and Greenland in the period 1992–1998.

shore areas and the basalt areas of Disko and Nuussuaq, was flown with a line spacing of 1000 m. The main line direction was north–south with control lines east–west at a spacing of 5000 m over the entire survey area. The survey altitude was kept as close to 300 m as possible by flying in a gentle drape defined by a digital terrain model and aircraft performance. The survey operations took place from 12 May 1997 to 25 July 1997 and were based at Ilulissat, the only airport in the area, using two aircraft for part of the time. For the first time in Greenland, the aircraft used were of the type Cessna 208B Grand Caravan (C-GSGY and C-GSGZ) which performed excellently. The principle instrument was a high sensitivity, caesium vapour magnetometer. During the 75-day field season 84 flights were required to collect the 70 630 line kilometres covering an area of approximately 46 187 km^2. Thus average production was 841 km per flight or 942 km per operational day. These excellent production figures reflect the limited problems with weather and equipment encountered during this survey.

The following parameters were measured digitally:

1. Airborne total magnetic field;
2. Aircraft altitude from barometric altimeter;
3. Terrain clearance from radar altimeter;
4. Airborne GPS data (latitude, longitude, height);
5. Ground total magnetic intensity;
6. Ground based GPS data (latitude, longitude, height);
7. Video tape recording of flight path.

Basic compilation scale was 1:50 000. The survey area has been divided into 35 map sheets and for each of these four maps are produced: Flight Line maps, Total Magnetic Intensity anomaly maps in colour, Total Magnetic Intensity as contour maps, and First Vertical Derivative of Total Magnetic Intensity as colour anomaly maps. Overview maps are at a scale of 1:250 000 (two map sheets) and 1:500 000 (one map sheet) include the same range of maps supplemented by shadow anomaly maps of various types. The combination of radar altimeter and differential GPS was used to calculate a model of terrain heights along lines and combine the information into a Digital Terrain Model in the form of a regular grid. This is only displayed at scale 1:500 000. More details about the instrumentation and its calibration, the acquisition of data, and the compilation and presentation of data can be seen in Murphy & Coyle (1997).

The complicated and varied geology of this region in central West Greenland encompasses Precambrian crystalline rocks, Cretaceous sedimentary basins and a major Tertiary basalt province. The new aeromagnetic maps and digital data have added substantial detail and regional coherence to the geophysical expression of the geology. As noted above, the results from Aeromag 1997 will be of considerable interest for the hydrocarbon exploration in the area (see Christiansen *et al.* 1998, this volume). A brief discussion of some of the many interesting features in the magnetic data is included in Thorning (in press).

Project AEM Greenland 1997: central East Greenland

As with project Aeromag 1997, the area selected for the AEM Greenland 1997 survey is theoretically prospective for both minerals and hydrocarbons. The survey block is located in northern Jameson Land, central East Greenland (Fig. 1). The highly variable topographic relief limited survey coverage in the region to the areas that could be safely flown. Nevertheless, some extremely interesting airborne geophysical results were released to the public on 1 March 1998.

The Jameson Land Basin is a thick sequence of Upper Palaeozoic and Mesozoic continental and marine sediments which have been invaded by a large number and variety of Tertiary intrusions (Henriksen 1986). The area has a mining history, as Nordisk Mineselskab A/S commercially mined the Blyklippen lead-zinc deposit in the period 1956–1962. Known mineral occurrences in the region are well documented by Harpøth *et al*. (1986).

Constable Pynt airport served well as the operational base for the field survey and also for the preliminary compilation and interpretation of the results. The airport was serviced by two regularly scheduled flights per week from Iceland during the survey period. Weather was reasonable by Greenland standards, and fog was not a problem compared to conditions during earlier survey operations in parts of South and West Greenland.

Geoterrex-Dighem Ltd. of Ottawa, Canada operated a Casa aircraft (C-FDKM) equipped for transient electromagnetic (GEOTEM) and magnetic surveying (Fig. 2). A total of 14 622 line kilometres of data were acquired, including two east–west reconnaissance lines flown north of the survey area at approximate latitudes of 72°35′N and 73°15′N.

The main survey covers a 5 227 km^2 large area. Lines were oriented east–west at 400 m intervals with north–south tie lines spaced at four kilometre intervals. Mean terrain clearance of the aircraft was 120 m, subject to flight crew safety in areas of rugged topography. GPS navigation with differential post-flight processing provided the required flight path accuracy.

The airborne geophysical equipment consisted of a GEOTEM time domain (transient) electromagnetic system and a high sensitivity, caesium vapour magnetometer. The latest, three-receiver coil version of GEOTEM was utilised. The aircraft was also equipped with radar and barometric altimeters plus a colour video camera.

Data acquisition was carried out in the period 11 July – 24 August 1997, a total of 45 days including 26 production days, 13 standby days for weather or diurnal disturbances and six unserviceable days. These statistics compare favourably with earlier AEM surveys in Greenland, i.e. 50–60% production days. Average flight duration for the Casa aircraft was 4.1 hours, yielding an average production per flight of approximately 375 km.

Fig. 2. The Geoterrex-Dighem Ltd CASA aircraft being inspected by the Danish Minister of Research, Jytte Hilden (right) and the Greenland Home Rule Government Minister for Research, Marianne Jensen (left), at Constable Pynt airport. This aircraft was used for the AEM Greenland 1997 GEOTEM survey.

Thirteen map sheets at a scale of 1:50 000 cover the survey area as the primary compilation scale. Various maps were also compiled at 1:250 000, 1:500 000 (flight path location only) and 1:900 000 (A4 report size). Multichannel stacked profiles of all parameters were produced for individual flight lines at 1:50 000 scale.

Map presentations include the following:

1. GEOTEM anomalies with flight lines;
2. GEOTEM x-coil channel 12 amplitude;
3. Conductance based on z-coil GEOTEM data;
4. Total magnetic intensity;
5. Magnetic vertical gradient;
6. Grey shadow of total magnetic intensity;
7. Colour shadow of total magnetic intensity;
8. Colour drape of x-coil channel 12 amplitude over shadow relief of total magnetic intensity;
9. Digital terrain model (DTM).

The digital terrain model is an interesting ancillary product of an airborne geophysical survey created using radar altimeter and GPS elevation data.

Comprehensive information on survey equipment, specifications and data processing is available in a report by Geoterrex-Dighem Ltd. (1997) which is provided with each data purchase and is available for viewing at the Survey's offices in Copenhagen.

A survey report (Stemp 1998) provides a detailed list of specific GEOTEM conductors recommended for ground follow-up as well as an insight into both regional and local magnetic variations in the survey block, including the possible discovery of new hidden, probably Tertiary intrusions south of the Werner Bjerge complex.

In summary, year four, of the planned five-year programme, project AEM Greenland 1994–1998, continued the success of earlier years. This was the first airborne electromagnetic survey carried out in East Greenland and also the first such survey over non-Precambrian geology in the area. The growth of the geophysical database is a key ingredient in the future development of exploration in Greenland. In addition to the surveys planned for the final year of Project AEM Greenland 1994–1998, in 1998 GEUS will also carry out limited ground follow-up of interesting anomalies in the AEM Greenland 1997 survey area financed by the Government of Greenland.

Acknowledgements

Project AEM Greenland 1997 and Project Aeromag 1997 would not have been possible without the financial support by the Government of Greenland and the foresight and support of the Minerals Office (*now* Bureau of Minerals and Petroleum) in Nuuk, Greenland. Thanks are due to Sander Geophysics Ltd., Geoterrex-Dighem Ltd., and their field crews for fulfilling all aspects of their contracts in a professional and timely manner. The staffs of the airports at Ilulissat and Constable Pynt provided invaluable assistance during the field operations; the authors would like especially to thank Benny Mouzinsky.

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Carbonate-hosted Zn-Pb-Ag mineralisation in Washington Land, western North Greenland

Sven Monrad Jensen

The multidisciplinary research project ‘Resources of the sedimentary basins of North and East Greenland’ was initiated in 1995 with financial support from the Danish Research Councils (Stemmerik *et al.* 1996). In 1997, North Greenland field studies under this project were carried out by the Geological Survey of Denmark and Greenland (GEUS) in Washington Land. A two-week field season included sedimentological and petroleum geology-related studies, and reconnaissance exploration for economic mineral occurrences.

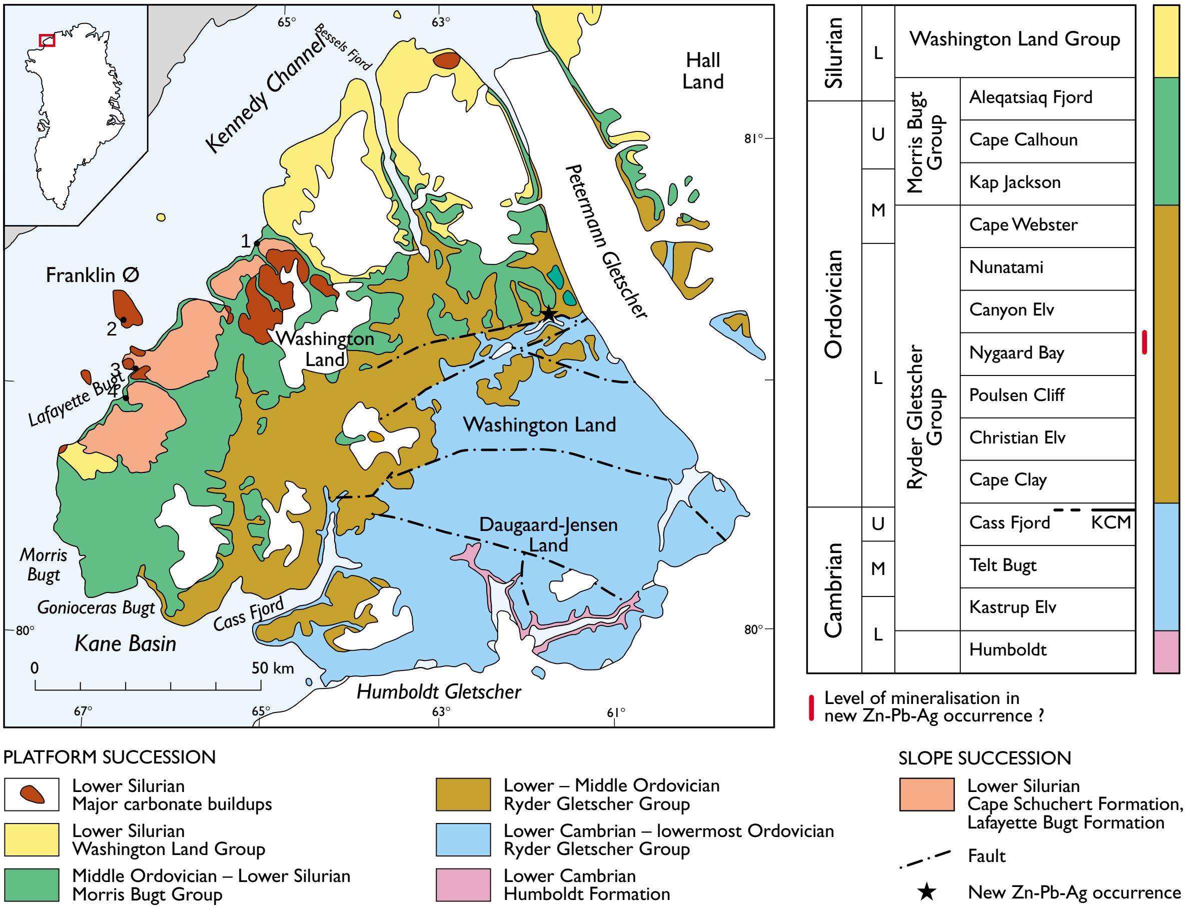

Fig. 1. Geological map of Washington Land, modified after Jepsen *et al.* (1983) and Bengaard & Henriksen (1991). A star shows the location of the new Zn-Pb-Ag occurrence. The only previously known sulphide occurrence (Norford 1972) is located at Kap Schuchert (locality 1). Finds of boulders with sphalerite (or hydrozincite) or galena are numbered 2–4. **Right**: Cambrian – Lower Silurian platform stratigraphy of Washington Land, after Higgins *et al.* (1991). Red bar indicates speculative stratigraphic level of mineralisation in the new Zn-Pb-Ag occurrence. KCM: Kap Coppinger Member.

Fig. 2. New Zn-Pb-Ag occurrence, eastern Washington Land: aerial photograph looking north-north-west over the central part of the train of rusty weathering patches (indicated by dashed line). Width of view is *c.* 500 m.

Washington Land is made up of Cambrian – Lower Silurian carbonate platform and Lower Silurian reef belt successions of the Franklinian Basin. In northern Canada, platform carbonates of the Franklinian Basin host a major producing Zn-Pb deposit (Polaris) and several other sulphide occurrences (Kerr 1977; Gibbins 1991). The platform succession in North Greenland has received less attention from an exploration point of view, and to date only a few, scattered carbonate-hosted sulphide occurrences have been discovered (Jakobsen & Steenfelt 1985; von Guttenberg & van der Stijl 1993; Lind *et al.* 1994). One sulphide occurrence was known in Washington Land prior to the 1997 field work (Norford 1972; Lind *et al.* 1994).

Cambrian – Lower Silurian carbonate platform

Discovery of a new Zn-Pb-Ag occurrence

One of the prospecting targets in Washington Land was fault-related Zn-Pb mineralisation in the carbonate platform succession. A number of roughly E–W trending regional-scale faults transect east-central and southern Washington Land, as marked on the 1:250 000 geological map (Jepsen *et al.* 1983) which forms the basis of Figure 1. An approximately 15 km wide, WSW–ENE trending corridor between central Washington Land and Petermann Gletscher was thought to be a promising area in which to look for signs of fault-related mineralisation.

A new Zn-Pb-Ag occurrence was discovered in eastern Washington Land during helicopter reconnaissance, *c.* 8 km west of Petermann Gletscher (Fig. 1). The surface expression of the mineralisation is a train of rusty weathering patches on a gently sloping plain covered by soliflucted mud and frost-heaved blocks (Fig. 2). The plain lies on the north shore of a 9–10 km long, narrow lake in the foothills of the ice-capped mountains of northern Washington Land. To the south of the lake lies a large plateau of poorly exposed Cambrian carbonate rocks.

The train of rusty weathering patches was followed over a 2.4 km long and approximately 100 m wide NE–SW trending zone. A dozen patches with diameters of 3–30 m were distinguished. The greatest density of patches is just east of the N–S flowing stream that cuts a shallow gorge into bedrock (Fig. 2).

Mineralisation

Dolomitic boulders variably mineralised with sphalerite, galena and pyrite were found within the rusty weathering patches (Fig. 3). The mineralised samples collected are strongly dolomitised and show very variable sulphide parageneses. Both pyrite-dominated, sphalerite-galena-dominated and pyrite-sphalerite-galena-rich mineralised rocks were found within most patches. Due to prolonged subaerial exposure the mineralised samples are rarely fresh.

Zinc mineralisation was revealed in the field either by visible sphalerite or a strong Zn spot test reaction. The sphalerite occurs most commonly as large (0.5–5

Fig. 3. New Zn-Pb-Ag occurrence, eastern Washington Land: rusty weathering outcrop of sulphide-rich, dolomitised limestone. Note seated person at left for scale.

Fig. 4. New Zn-Pb-Ag occurrence, eastern Washington Land: cut slab of boulder sample. Coarse-grained dolomite with large sphalerite aggregates – note colloform-banded pyrite and sphalerite in central part of slab (sample GGU 447027: 15% Zn, 0.4% Pb).

cm) aggregates, but can also be found fine-grained and disseminated. The colour varies from dark brown to honey coloured. Galena is often present as large (5–10 mm), relatively fresh euhedral grains. Pyrite occurs with a range of textures, from very fine-grained and massive to colloform-banded (Fig. 4) or coarse-grained aggregates. Bitumen with vitreous lustre was found in a few mineralised samples near the stream, occupying vugs in coarse-grained, sparry dolomite.

Judging from outcrops along the stream, the sulphide mineralisation is associated with a pervasively dolomitised horizon of 6–8 m thickness. Sulphide-rich pods occur very irregularly, and appear to be concentrated in the upper parts of the dolomitised horizon. The *in situ* mineralisation observed is generally pyrite-dominated.

Sampling and analyses

Samples from the rusty weathering patches are all strictly speaking loose blocks, but are believed to have lain directly above, or within a few metres distance of their original bedrock position (Fig. 3). Only the samples collected along the stream are true bedrock samples. One or two composite samples of *c.* 3 kg size were collected from each of the rusty weathering patches.

Visually estimated Zn and Pb grades vary from close to nil to over 20% Zn and 10% Pb. Multi-element neutron activation (INAA) and inductively coupled plasma emission (ICP) analyses of 23 samples have indicated several anomalous Ag values, with a maximum of *c.* 170 ppm. Subsequent assays of eight samples have confirmed the highest Zn, Pb and Ag values. The mineral-

Table 1. Summary of zinc, lead, silver and iron analyses of boulder samples from the new Zn-Pb-Ag occurrence, eastern Washington Land

Sample GGU no.	Zn* %	Pb* %	Ag* ppm	Fe† %
447018	2.85	2.94	31	2.40
447021	1.25	0.18	1.6	12.1
447022	0.22	0.03	1.4	22.6
447023	8.21	0.01	20	24.8
447024	0.04	0.01	0.4	34.7
447025	0.03	0.001	0.5	2.09
447026	0.06	0.64	0.4	4.44
447027	15.3	0.41	–	6.89
447028	0.34	0.06	4.4	6.71
447029	0.66	7.67	2.5	9.80
447030	0.20	0.02	3.7	1.76
447033	24.5	12.70	170	4.96
447034	0.08	0.03	1.3	18.2
447035	3.27	0.01	1.6	1.35
447036	0.53	0.02	2.3	15.2
447037	0.38	0.004	0.9	5.29
447038	0.20	0.01	0.7	33.6
447040	0.12	0.18	1.4	25.4
447043	0.72	0.01	–	32.7
447044	0.09	0.01	–	42.9
447045	0.01	0.005	–	37.2
447046	0.01	0.01	–	27.1
447047	0.03	0.01	–	30.0
mean	2.57	1.09	14	17.5
median	0.22	0.02	1.6	15.2
standard deviation	5.92	3.03	41	13.5

– below detection limit of 0.4 ppm;
* estimated from INAA, ICP and assay values;
† Fe is total iron determined by INAA.
Analyses by Activation Laboratories Ltd., Ancaster, Ontario, Canada.

isation is further characterised by high Cd and Hg contents (Cd up to 841 ppm, median 10 ppm, 19 analyses; Hg up to 47 ppm, median 11 ppm, 7 analyses). Analyses for Zn, Pb, Ag and Fe are summarised in Table 1; the full analytical data set is given in Jensen & Schønwandt (1998).

Although the higher grades are generally found near the intersection of the stream and the train of rusty weathering patches, the best mineralised sample (447033) was collected at the far south-western end of the mineralised zone, about 2 km south-west of the main cluster of patches.

Geological setting

The sedimentary succession in the area around the new Zn-Pb-Ag occurrence has a shallow dip to the north-west, with measured orientations of bedding planes of 025–035°/5–15°NW. On the published 1:250 000 geological map (Jepsen *et al.* 1983), the sulphide occurrence is seen to lie within the upper part of a mapped unit comprising the Poulsen Cliff and Nygaard Bay Formations (Ryder Gletscher Group). The exact stratigraphic position of the dolomitisation and sulphide mineralisation remains to be established, but seems likely to be within the evaporitic upper part of the Nygaard Bay Formation (Fig. 1).

The main cluster of rusty weathering patches lies about 1 km north of the projected trace of a regional E–W striking fault (Fig. 1). The trace of the regional fault was not observed directly in the field, but is shown on the 1:250 000 geological map (Jepsen *et al.* 1983). At the far south-western end of the mineralised trend, a 6–8 m wide faulted zone (048°/58°N) is exposed for *c.* 10 m along strike. This faulted zone is oblique to the regional fault, but aligned roughly with the mineralised trend.

Tentative model

The new Zn-Pb-Ag occurrence is hosted by the partly evaporitic, Lower Ordovician part of the carbonate platform succession. One can speculate that hydrothermal fluids carrying metals in solution migrated up along fault planes and that sulphides precipitated where dolomitisation created open space and sulphur was available. The sulphur was perhaps derived from the evaporite beds. For this sulphur to have been incorporated into sulphides, a mechanism to reduce SO_4^{2-} to S^{2-} must have been available. The presence of bitumen in some of the sulphide-mineralised samples suggests that thermochemical sulphate reduction may have taken place, at least very locally. The source of metals is suggested to have been the underlying Lower Cambrian siliciclastic sequence (Humboldt Formation) or perhaps the crystalline basement.

Lower Silurian reef and slope succession

Kap Schuchert

Mineralisation at Kap Schuchert (locality 1 in Fig. 1) was discovered in 1966 during joint Geological Survey of Canada and Geological Survey of Greenland field work in North Greenland and Ellesmere Island, Canada (Norford 1972). The results of a brief visit to the locality in 1971 by Cominco geologists did not warrant follow-up (Cominco Ltd. 1971).

Analyses of three mineralised vein samples collected at the locality in 1997 are listed in Table 2. All three samples show anomalous silver contents. Sample 447013 is from a 5 cm wide and 10 m long sulphide-bitumen-rich quartz-calcite vein that was also described by Norford (1972). The mineralised rocks are brownish, nodular weathering limestones with a distinct petroliferous odour. Sulphide-filled vugs (Norford 1972) and sulphide-bitumen-rich, small veins occur in the brownish limestone unit. Overlying light grey crinoidal limestones and calcarenites appear to have formed a 'lid' over the hydrocarbon-impregnated unit, and are only mineralised where breached by vertical joints or small veins.

Table 2. Summary of zinc, lead, silver and iron analyses of boulder samples from the Lower Silurian reef and slope succession

Sample GGU no.	Locality, Fig. 1	Zn† %	Pb† %	Ag† ppm	Fe‡ %
100825*	1	1.5	2.0	36	0.14
447013*	1	4.6	1.3	37	24.0
447016	1	0.02	0.07	6.6	12.1
447017	1	0.01	0.04	5.0	9.05
447008	2	0.12	0.03	6.5	0.11
447005	3	0.20	0.003	–	0.19
447004	4	0.73	0.20	–	0.11

– below detection limit of 0.4 ppm;
* sample 447013 is from the same vein as Norford's (1972) sample 100825;
† estimated from INAA, ICP and assay values;
‡ Fe is total iron determined by INAA.
Analyses by Activation Laboratories Ltd., Ancaster, Ontario, Canada.

Scattered mineralised boulders

A few boulders with minor amounts of sphalerite or galena were collected along rivers draining Lower Silurian reef and slope complexes exposed on the coast of Kennedy Channel (localities 2–4 in Fig. 1). None of the boulders were traced back to bedrock mineralisation. Sample 447008, collected on Franklin Ø, is anomalous with respect to silver (Table 2). The boulder samples probably represent mineralisation similar to that found at Kap Schuchert.

Regional perspective

The decision to look for fault-related, carbonate-hosted mineralisation in east-central Washington Land arose from consideration of the geological setting of the Polaris Zn-Pb deposit in Canada (located *c.* 900 km south-west of Washington Land). Without wishing to suggest the new Zn-Pb-Ag occurrence to even remotely approach Polaris-class mineralisation, the two areas share several characteristics that may relate to their ore genesis (based on Polaris descriptions from Randell & Anderson 1990; Gibbins 1991; Sharp *et al.* 1995): (1) overall stratigraphic setting, (2) faults may have provided channels for metal-bearing fluids from a source in the basement or underlying siliciclastic units, (3) evaporitic units may have been the source of sulphate ions, (4) hydrocarbons may have caused thermochemical reduction of sulphate to sulphide, (5) extensive dolomitisation of host rocks.

The overall stratigraphy of the Cambrian–Ordovician platform of Washington Land has been correlated with that of eastern Ellesmere Island (Peel & Christie 1982), and areas farther south-west (Trettin *et al.* 1991; de Freitas *et al.* 1997). The Washington Land occurrence is, however, not hosted by the western North Greenland correlative to the Thumb Mountain Formation, Polaris' host rock. The Thumb Mountain Formation correlates in Washington Land with the Kap Jackson Formation (Morris Bugt Group, Fig. 1; Peel & Christie 1982; Smith *et al.* 1989). Although mineralisation at occurrence or deposit scale seems to be restricted to certain stratigraphic levels, this is not necessarily the case at regional scale, as illustrated by recent discoveries in the vicinity of the Polaris deposit (Harrison & de Freitas 1996).

Of a total of 37 analysed samples from Washington Land, 26 have shown detectable Ag (0.4 ppm or more), 16 over 1 ppm, 9 over 5 ppm, and 3 over 30 ppm, with a maximum of *c.* 170 ppm. Mineralisations in both the carbonate platform and the reef and slope successions, at localities up to 100 km apart, are thus characterised by somewhat anomalous silver contents. Mineralisations in the reef and slope succession differ geochemically from that of the new Zn-Pb-Ag occurrence in the carbonate platform in having anomalous As, Mo, Ba, Sr, V and REE contents, but no Hg enrichment.

Follow-up

The airborne geophysical survey 'AEM Greenland 1998', financed by the Government of Greenland and managed by GEUS, will include an about 9500 line kilometre GEOTEM/magnetic survey over east-central Washington Land, encompassing the new Zn-Pb-Ag occurrence and several prospective regional fault zones (Thorning & Stemp 1998, this volume).

Acknowledgement

T.I. Hauge Andersson, Danish Polar Center is thanked for organising the logistics of the 1997 field work in Washington Land.

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Karrat 97: reconnaissance mineral exploration in central West Greenland

Agnete Steenfelt, Bjørn Thomassen, Mogens Lind and Johannes Kyed

The Karrat 97 project aims at the acquisition of geochemical data from drainage samples and information on mineralisation within a 10 000 km^2 area, which stretches from Uummannaq northwards to Prøven (i.e. from 70°30′ to 72°30′ N; Fig. 1). The project area comprises a major Palaeoproterozoic supracrustal unit, the Karrat Group, from which the project takes its name, and which hosts the abandoned Black Angel lead-zinc mine. It is a joint project 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 goal of the project is to win back the interest of the mining industry to the area.

The eastern part of the project area is difficult of access due to alpine topography with peaks up to 2300 m, abundant glaciers, and steep-sided, often ice-filled fjords. A somewhat more gentle topography prevails in the western parts of the area. The whole area is underlain by permafrost.

Field work was carried out during seven weeks in July–August 1997 by a team of four geologists and four local prospectors. Job-training of the prospectors was an integral purpose of the project, and the manning of the teams was periodically changed so that all four prospectors were introduced to the different topographical and geological terrains in the area as well as to the methods of operation. A chartered 68 foot, 77 tons vessel – M/S *Nukik* – served as mobile base with accommodation and meals on board; a MD 500 E helicopter with crew chartered through Grønlandsfly A/S participated for one month. The work was carried out from five anchorages, with the helicopter stationed on the adjacent coast. The weather was relatively unstable in the field period, but only five days of work were lost due to bad weather.

The field work comprised regional-scale systematic drainage sampling, and detailed mineral exploration at selected sites. The sampling of stream sediment and stream water supplements the geochemical mapping programme of Greenland undertaken jointly by GEUS and BMP (Steenfelt 1993, 1994), the aim of which is to provide systematic, quality controlled geochemical data. The data are used together with geological and geophysical information in the evaluation of the potential for economic mineral resources. Samples were collected by two teams, transported by helicopter or small boats. All ice-free, near-coastal localities were sampled by the boat team, whereas all other localities were sampled by the helicopter team. The results of this work have been reported on by Steenfelt *et al.* (1998).

The detailed mineral exploration was follow-up work on previously outlined indications and anomalies. It was carried out by two teams on daily trips by rubber dinghy or helicopter, or by foot traverses from field camps. This part of the project has been reported on by Thomassen & Lind (1998).

Geological setting

The area between Uummannaq and Prøven comprises four main litho-stratigraphic units: Archaean basement dominated by tonalitic gneisses, a several kilometres thick succession of Palaeoproterozoic metasediments, a Palaeoproterozoic granite intruding the metasediments, and Tertiary plateau basalts (Fig. 1). In addition, there are minor units of down-faulted Cretaceous sediments. The first three units are transected by 1.65 Ga old dolerite dykes. The area is covered by two geological maps at scale 1:500 000, published by the Survey, and most of the area, except the north-western corner, are covered by 6 geological map sheets at scale 1:100 000.

The Archaean rocks comprise a complex of tonalitic to granodioritic grey gneisses with occasional intercalated supracrustal units and mafic to ultramafic bodies.

The Palaeoproterozoic sediments, the Karrat Group (Henderson & Pulvertaft 1967, 1987), overlie the Archaean

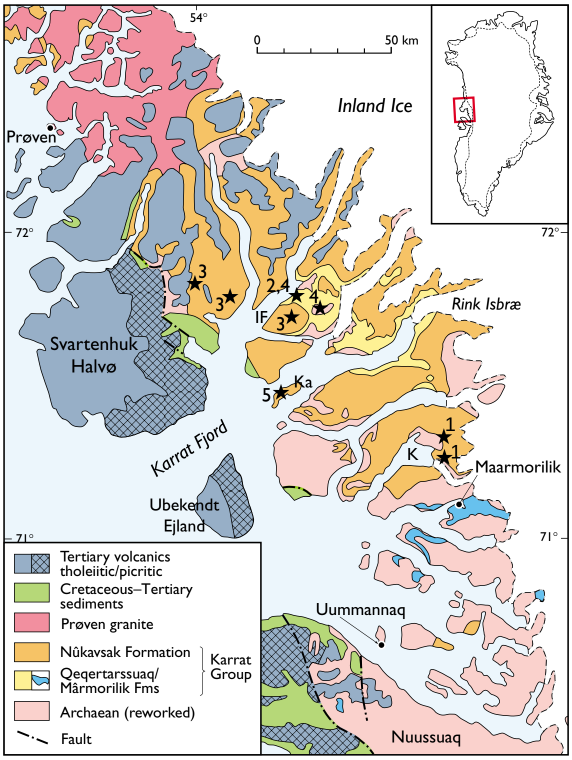
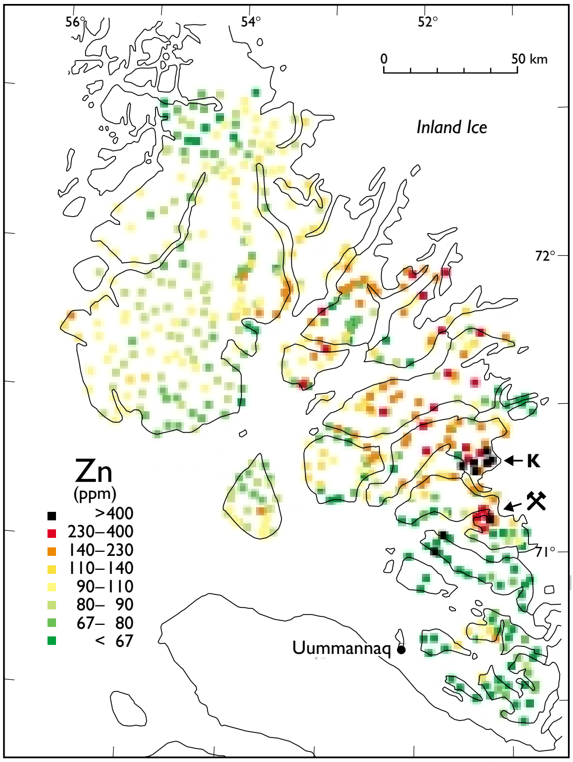


Fig. 1. Geological map of the Uummannaq–Prøven area, based on Grocott & Pulvertaft (1990). IF: Inngia Fjord; K: Kangerluarsuk, Qaarsukassak; Ka: Karrat island. Stars 1 to 5 indicate mineral localities discussed in the text.



Topographic base G/2.5 M Vector, © KMS/GEUS 1997

Fig. 2. Geochemical map of Zn concentrations in the < 0.1 mm fraction of stream sediment samples. K: Kangerluarsuk. Position of the abandoned lead-zinc mine at Maarmorilik is indicated by the mine symbol.

basement over a 500 km long stretch of coast from 70°30′ to 75°00′ N. The sequence was laid down in an epicontinental environment, and comprises minor platformal units and a major basinal turbidite flysch succession with a minimum structural thickness of 5 km (Grocott & Pulvertaft 1990). Based on U-Pb isotope data on detrital zircons it is estimated that the deposition, of at least the basinal facies, took place around 2 Ga ago (Kalsbeek *et al.* 1998). The carbonate-dominated Mârmorilik Formation occurs in the southern part of the area, whereas the mainly siliciclastic Qeqertarssuaq Formation occurs further to the north. The uppermost part of the latter comprises hornblende schist and amphibolite, interpreted as flows and tuffs, and commonly minor carbonate. The two formations are overlain by the Nûkavsak Formation, which is dominated by dark coloured (grey, brown, black), alternating pelitic and semipelitic schists (greywackes) with occasional graphite-pyrrhotite-rich horizons.

During the Rinkian (Hudsonian) orogenesis around 1.85 Ga the basement and cover sequence were subjected to strong folding and thrusting, and the rocks were variably affected by high temperature-low pressure metamorphism (Grocott & Pulvertaft 1990). The resulting structural pattern is characterised by mantled gneiss antiforms and displacements on low-angle detachment zones. A syn-tectonic, hypersthene-bearing granite body, the Prøven granite, was intruded north of Svartenhuk Halvø, and has given a Rb-Sr age of 1.86 ± 0.25 Ga (Kalsbeek 1981).

The mafic lavas and subordinate sedimentary rocks in the western and northern part of the project area form part of the Tertiary volcanic province of West Greenland (Clarke & Pedersen 1976). The genesis of the province of plateau basalts has been related to the same hot mantle plume which was responsible for the creation of the North Atlantic Tertiary igneous province (Upton 1988). The lava series occurring at Svartenhuk Halvø and Ubekendt Ejland comprises basal picritic breccias and olivine-rich lavas followed by a thick sequence of feldspar-phyric basalts (Clarke & Pedersen 1976). The Tertiary igneous rocks also comprise a granite at

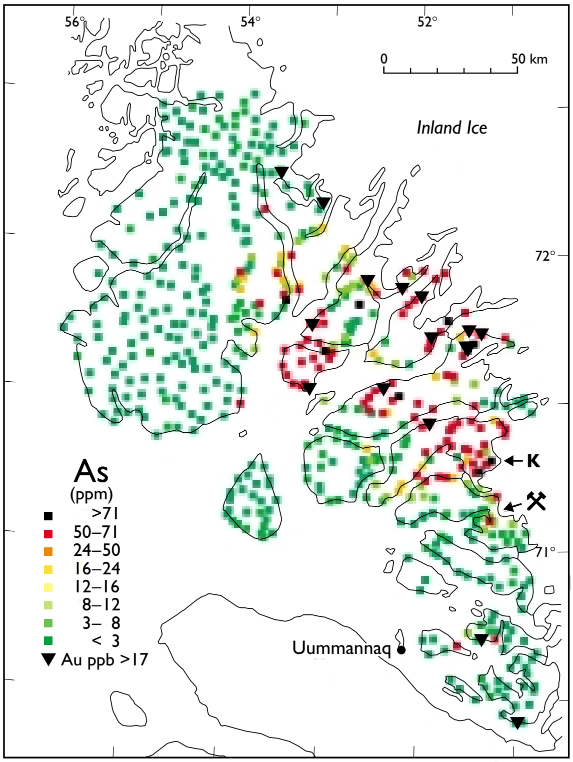


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Fig. 3. Geochemical map of As concentrations in the < 0.1 mm fraction of stream sediment samples. The black triangles show sites with Au concentrations equal to or above the 98th percentile of the Au values. Letter and mine symbol as in Fig. 2.

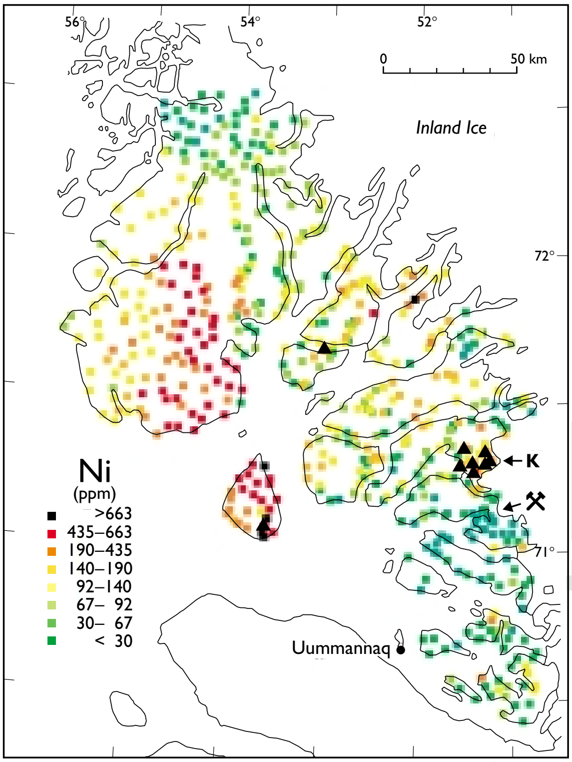

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Fig. 4. Geochemical map of Ni concentrations in the < 0.1 mm fraction of stream sediment samples. The black triangles indicate sites where Ni is enriched relative to MgO, the sample points marked as triangles in Fig. 5. Letter and mine symbol as in Fig. 2.

Ubekendt Ejland and a number of thin lamprophyric dykes throughout most of the survey region.

Geochemical reconnaissance exploration and mapping

The stream sediment samples were collected with an average density of 1 sample per 15 to 20 km^2. Prior to the field work preferred sample sites were selected and marked on aerial photographs. It was attempted to obtain an even distribution of sample localities located in first or second order streams with drainage basins not larger than 10 km^2.

The fine fractions (< 0.1 mm) of the stream sediment samples have been used for analysis. Major elements were determined by X-ray fluorescence spectrometry using fused samples, trace elements were determined by a combination of instrumental neutron activation analysis and inductively coupled plasma emission spectrometry.

The total number of localities sampled for the geochemical mapping was 528. Samples from 44 previously sampled localities are also included in the survey. The distribution of the sites are seen in the geochemical maps (Figs 2–4), and Table 1 contains simple statistical parameters for the analytical data.

Preliminary results

Element distribution maps have been produced for forty elements (Steenfelt *et al.* 1998), three of which are presented here as examples (Figs 2–4). Figure 2 demonstrates how the distribution pattern of Zn reflects major lithological provinces: low Zn in the Archaean gneisses and the Prøven granite, medium Zn in the Tertiary lavas. Within the Karrat Group the Zn is unevenly distributed with high Zn in the Mârmorilik Formation, low in the Qeqertarssuaq Formation and scattered high concentrations in streams derived from the south-central parts of the Nûkavsak Formation. The highest Zn concentrations outside the Black Angel mining area are located

Table 1. Statistical parameters for major and trace elements of stream sediment samples between Uummannaq and Prøven, West Greenland

	Min.	Max.	Med.	98 pc.	An. meth.
SiO_2	8.89	76.02	62.14		XRF
TiO_2	0.05	4.92	0.88		XRF
Al_2O_3	1.29	19.52	13.64		XRF
Fe_2O_3	1.48	26.05	8.92		XRF
MnO	0.03	0.39	0.11		XRF
MgO	0.73	28.65	3.75		XRF
CaO	0.47	78.4	3.9		XRF
Na_2O	0.31	4.41	2.09		XRF
K_2O	0.07	4.64	1.99		XRF
P_2O_5	0.05	0.88	0.17		XRF
As	0	190	2.9	71	INAA
Au (ppb)	<2	61	0	18	INAA
Ba	<100	5500	450	1000	INAA
Co	1	130	27	74	INAA
Cr	<5	5400	170	2600	INAA
Cu	5	776	107	285	ICP-ES
Hf	<1	110	6	24	INAA
Mo	<2	35	0	11	ICP-ES
Ni	5	804	91	620	ICP-ES
Pb	<5	327	19	62	ICP-ES
Rb	<5	240	61	150	INAA
Sb	<0.1	7.5	0	1.8	INAA
Sc	0.5	61	18	50	INAA
Sr	68	423	164	296	ICP-ES
Th	<0.2	90	11	50	INAA
U	<0.5	230	3.4	39	INAA
V	7	611	142	483	ICP-ES
Y	5	202	24	51	ICP-ES
Zn	21	1483	91	344	ICP-ES
La	2.2	610	42	216	INAA
Ce	4	970	77	312	INAA
Nd	<5	550	28	140	INAA
Sm	0.3	95	5.8	23	INAA
Eu	<0.2	15.1	1.3	3.3	INAA
Yb	<0.2	18	2.7	5.6	INAA
Lu	<0.05	2.8	0.4	0.9	INAA

Analytical methods (An. meth.) for the < 0.1 mm grain size fraction of 572 stream sediment samples. XRF: X-ray fluorescence spectrometry, INAA: instrumental neutron activation analysis, ICP-ES: inductively coupled plasma emission spectrometry.
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.

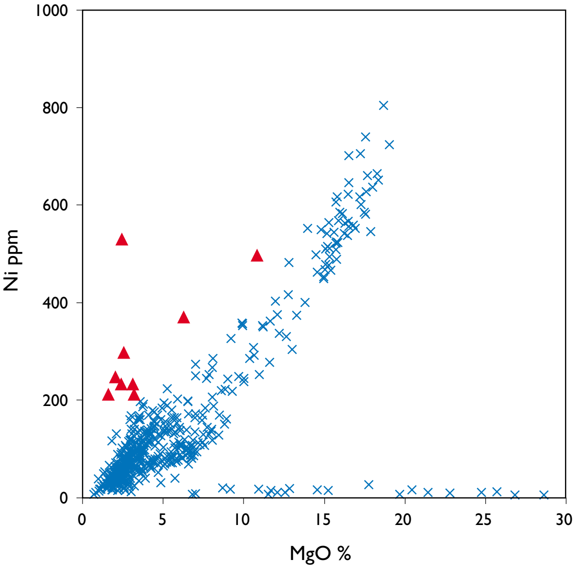

Fig. 5. Ni concentrations versus MgO concentrations in stream sediment samples. The strong correlation illustrates that most of the Ni occurs in Mg-bearing silicate minerals. The high MgO-low Ni samples are derived from dolomites of the Mârmorilik Formation. Samples with excessive Ni, red/filled triangles, are likely to contain Ni-sulphides.

in the area east of Kangerluarsuk (K in Fig. 1) in the lowermost part of the Nûkavsak Formation. The highest Zn value obtained in this district is 1483 ppm.

The south-central part of the Nûkavsak Formation is also characterised by high concentrations of As (Fig. 3), whereas all other units are low in As. Twelve of the sixteen samples with elevated gold concentrations are located within the high As province. The two parallel north-western trends of the gold anomalies are parallel with the dominating structural trends, and a possible gold mineralisation is tentatively considered to be structurally controlled. There is a small cluster of samples with high As values and one Au anomaly in the south, associated with an infolded remnant of the Nûkavsak Formation in the otherwise gneiss dominated terrain.

The map of Ni (Fig. 4) shows high concentrations in a belt across Svartenhuk Halvø and Ubekendt Ejland, which reflect the olivine-rich breccias and lavas of the Vaigat Formation (Pedersen 1985) in the lower part of the Tertiary plateau basalt sequence on Svartenhuk Halvø. The strong correlation between MgO and Ni in most of the samples, illustrated by the scatter diagram (Fig. 5), demonstrates that the Ni is, indeed, associated with olivine. From an economic point of view the high concentrations of olivine-bound Ni are not immediately interesting. However, samples showing Ni enrichment relative to MgO, marked by red triangles in the diagram, are likely to contain Ni in sulphide phases. The locations of these samples are shown by the black triangles in Figure 4 that are seen to form a cluster east of Kangerluarsuk (K in Fig. 1), where also Zn values are high. This area therefore constitutes an interesting target for further prospecting.

Mineral occurrences and exploration activities

The field work comprised examination of known showings, follow-up of gold anomalies, and visits to selected localities of the Greenlandic minerals hunting project, Ujarassiorit (Dunnells 1995; Erfurt & Tukiainen 1997). The follow-up work included visual prospecting for mineralised float and outcrops on foot traverses, supplemented with local stream sediment sampling and panning. The collected samples were submitted for multi-element analysis including gold and base metals. Results are reported by Thomassen & Lind (1998).

Carbonate-hosted lead-zinc mineralisation is common in the Mârmorilik Formation. The Black Angel deposit, at Maarmorilik (Fig. 1), comprised ten ore bodies of commercial size, totalling 13.6 million tonnes grading 12.3% Zn, 4.0% Pb and 29 ppm Ag, of which 11.2 million tonnes were extracted in the period 1973–90 by Greenex A/S, a Danish company controlled by Cominco Ltd., and from 1986 by Boliden Mineral AB (Pedersen 1980, 1981; Thomassen 1991a). The massive sphalerite-galena-pyrite ores are hosted by calcitic and dolomitic marbles with intercalations of anhydrite-bearing marbles and pelitic schists. The origin of the ores is uncertain (Thomassen 1991a) as the sulphides are strongly tectonised and metamorphosed at greenschist facies conditions. The present ore distribution is structurally controlled. A number of similar galena-sphalerite-pyrite occurrences are known from the marble outcrops between Maarmorilik and Nuussuaq.

The Qeqertarssuaq Formation hosts scattered epigenetic copper mineralisation in quartzites and in the metavolcanic hornblende schists at the top of the formation. The copper showing at the east coast of Inngia Fjord (loc. 2 on Fig. 1, Fig. 6) was found by the Survey in 1989 (Thomassen 1991b). It consists of disseminated or blebby slightly auriferous chalcopyrite and pyrrhotite in a few centimetres thick quartz veins which have been followed laterally over 300 m and appear to be controlled by a thrust or flat-lying shear zone. The host rocks are quartzites with ultramafic lenses. The overall metal contents are low, but the style represents an interesting epigenetic exploration target, as thrusts and shear zones are abundant in the area. During the field visit, copper-bearing scree samples were found above the mineralised zone, which indicates that the mineralisation is more widespread than previously assumed.

Two mineralised samples collected in the neighbouring area (locs 4 on Fig. 1) stem from lateral moraines to glaciers transecting mainly Qeqertarssuaq Formation rocks. One is a 0.5 m sized boulder of tourmaline-bearing vein quartz with semi-massive, intergrown pyrite and pyrrhotite containing 649 ppb Au, 2100 ppm Co and 415 ppm Cu. The other is a mica schist with veinlets and blebs of pyrrhotite, pyrite, chalcopyrite and magnetite which returned 325 ppb Au, 510 ppm Co, 1212 ppm Cu, 630 ppm Th and 300 ppm U. These samples are indicative of epigenetic mineralisation with potential for gold in the Qeqertarssuaq Formation.

The hornblende schists of the Qeqertarssuaq Formation are often overlain by a 0.5–5.0 m thick, rusty-weathering horizon of graphite-pyrrhotite schist with conformable lenses and layers of semi-massive iron sulphides (Allen & Harris 1980; Thomassen 1991b). Similar horizons of sulphidic, graphitic and often cherty schists with lenses and layers of semi-massive, brecciated pyrrhotite, minor pyrite and traces of chalcopyrite are widespread in the Nûkavsak Formation. Such horizons may be 5–10 m thick and continue for 5–10 km along strike, and they seem to be most common in the lower part of the formation (Allen & Harris 1980).

The semi-massive, pyrrhotite-graphite mineralisation was sampled in outcrop and boulders at several localities. The values are comparable with previously reported values for this type of mineralisation (Thomassen 1992) although a zinc value of 0.9% is the highest recorded to date outside the Kangerluarsuk area. It stems from an outcropping rust zone on Karrat island (loc. 5 on Fig. 1).

Zinc showings were found by RTZ Mining and Exploration Ltd. in 1991, east of Kangerluarsuk (locs 1 on Fig. 1; Fig. 7; Coppard *et al.* 1992). The mineralisation is stratabound and consists of sphalerite, pyrrhotite and minor galena hosted by marbles, pelites and cherts near the base of the Nûkavsak Formation. The sulphides occur as recrystallised massive layers or lenses, as chert-pelite-sulphide lamina, and as disseminated grains in various host rocks (Fig. 8). The mineralisation occurs intermittently over a strike-length of some 9 km, and the best outcrop so far located is a 15–35 cm thick horizon of massive, dark brown sphalerite assaying 41% Zn which seems to be of limited lateral extent (Coppard *et al.* 1992).

Quartz veins with minor sulphides and occasionally elevated gold contents are common in the turbidite sequence of the Nûkavsak Formation, and a potential for epigenetic 'turbidite–hosted gold deposits' (Keppie *et al.* 1986) has been proposed by Thomassen (1992). Three gold-anomalous areas were delineated by the Survey on eastern Svartenhuk Halvø and south-east of Inngia Fjord (Thomassen 1993). The anomalies are

Fig. 6. Part of the east coast of Inngia Fjord displaying grey quartzites of the Qeqertarssuaq Formation conformably overlain by brown greywackes of the Nûkavsak Formation two thirds up the 1800 m high mountain ridge. The copper showing (2) and the location of the boulder of vein quartz (4), mentioned in the text, are indicated.

Fig. 7. Zinc showing at Qaarsukassak, east of Kangerluarsuk. The zinc mineralisation is hosted by the rusty metasediments in the foreground. In the background, light grey Archaean gneiss is overlain by typical dark brown Nûkavsak Formation greywackes. The contact is tectonic. View from the south-east. The relief shown is about 1000 m.

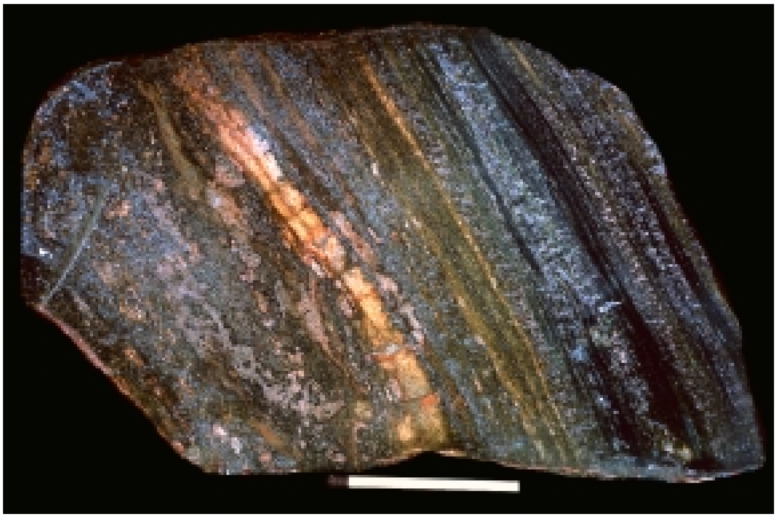

Fig. 8. Polished slab from the zinc showing at Qaarsukassak, east of Kangerluarsuk, displaying interbedded pelite, chert and sulphides (sphalerite, galena and pyrrhotite). The analysis gave 6.5% Zn, 0.2% Pb, 200 ppm Ag and 8.4% Fe. Matchstick, 4.5 cm.
Photo: Jakob Lautrup.

mainly defined by heavy mineral concentrates which yielded gold values in the parts per million range, whereas the gold response in stream sediment samples was modest. Two of the gold anomalies coincide with arsenic anomalies and are located within the Nûkavsak Formation. Parts of these anomalies were checked in the field on the assumption that gold is associated with arsenopyrite, the latter being the prospecting target. Boulders of vein quartz or metasediment with disseminated arsenopyrite were encountered in three areas (locs 3 on Fig. 1), and the highest element concentrations of 11 samples were 1083 ppb Au and 2.5% As. Native gold was observed microscopically in some of the samples forming up to 40 micrometre inclusions and vein-fillings in arsenopyrite.

Concluding comments

The stream sediment data from the Uummannaq to Prøven region represent the first systematic exploration at a regional scale over the entire district, and in the preliminary evaluation of the data two targets have appeared with potential for mineral deposits: (1) Qaarsukassak, east of Kangerluarsuk, with indications of base metal sulphides (Zn, Ni, Cu), and (2) the gold anomalous trends.

Zinc mineralisation had already been noted at Qaarsukassak (Coppard *et al.* 1992). However, the geochemical anomaly for Zn and sulphide-bound Ni is much larger than the known mineralisation, and therefore there is good reason to re-examine the area with detailed soil sampling and electromagnetic surveys.

The anomalous gold trend is a new feature which warrants field work and detailed rock and scree sampling to obtain more information of the geological setting and possible types of mineralisation. During the sampling at Rink Isbræ it was noticed that the uppermost part of the Qeqertarssuaq Formation consists of red coloured, well preserved, finely laminated beds which are overlain by tens of metres of black pelitic schist; the latter presumably belong to the Nûkavsak Formation although the ‘diagnostic’ amphibolite was not seen.

The mineral exploration part of the project has confirmed the existence of arsenopyrite-bearing rocks with elevated gold contents in parts of the Nûkavsak Formation. Until this mineralisation is found in outcrop, its economic significance cannot be determined. The locality of the sample with elevated zinc content on Karrat island invites closer inspection, and in general it is felt that the stratabound, pyrrhotite-dominated mineralisation in the Nûkavsak Formation deserves a systematic regional investigation.

Finds of boulders from the Qeqertarssuaq Formation with elevated concentrations of gold and other metals indicate an additional exploration target.

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Hydrothermal activity in the Upper Permian Ravnefjeld Formation of central East Greenland – a study of sulphide morphotypes

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Bituminous shales of the Ravnefjeld Formation were deposited in the subsiding East Greenland basin during the Upper Permian. The shales are exposed from Jameson Land in the south (71°N; Fig. 1) to Clavering Ø in the north (74°20′N) and have attracted considerable attention due to their high potential as hydrocarbon source rocks (Piasecki & Stemmerik 1991; Scholle *et al.* 1991; Christiansen *et al.* 1992, 1993a, b). Furthermore, enrichment of lead, zinc and copper has been known in the Ravnefjeld Formation on Wegener Halvø since 1968 (Lehnert-Thiel 1968; Fig. 1). This mineralisation was assumed to be of primary or early diagenetic origin due to similarities with the central European Kupferschiefer (Harpøth *et al.* 1986). Later studies, however, suggested base metal mineralisation in the immediately underlying carbonate reefs to be Tertiary in age (Stemmerik 1991). Due to geographical coincidence between the two types of mineralisation, a common history is a likely assumption, but a timing paradox exists. A part of the TUPOLAR project on the 'Resources of the sedimentary basins of North and East Greenland' has been dedicated to re-investigation of the mineralisation in the Ravnefjeld Formation in order to determine the genesis of the mineralisation and whether or not primary or early diagenetic base metal enrichment has taken place on Wegener Halvø, possibly in relation to an early period of hydrothermal activity. One approach to this is to study the various sulphides in the Ravnefjeld Formation; this is carried out in close co-operation with a current Ph.D. project at the University of Copenhagen, Denmark.

Diagenetically formed pyrite is a common constituent of marine shales and the study of pyrite morphotypes has previously been successful from thermalli immature parts of elucidating depositional environment and thermal effects in the Alum Shale Formation of Scandinavia (Nielsen 1996; Nielsen *et al.* 1998). The present paper describes the preliminary results of a similar study on pyrite from thermally immature parts of the Ravnefjeld Formation which, combined with the study of textures of base metal

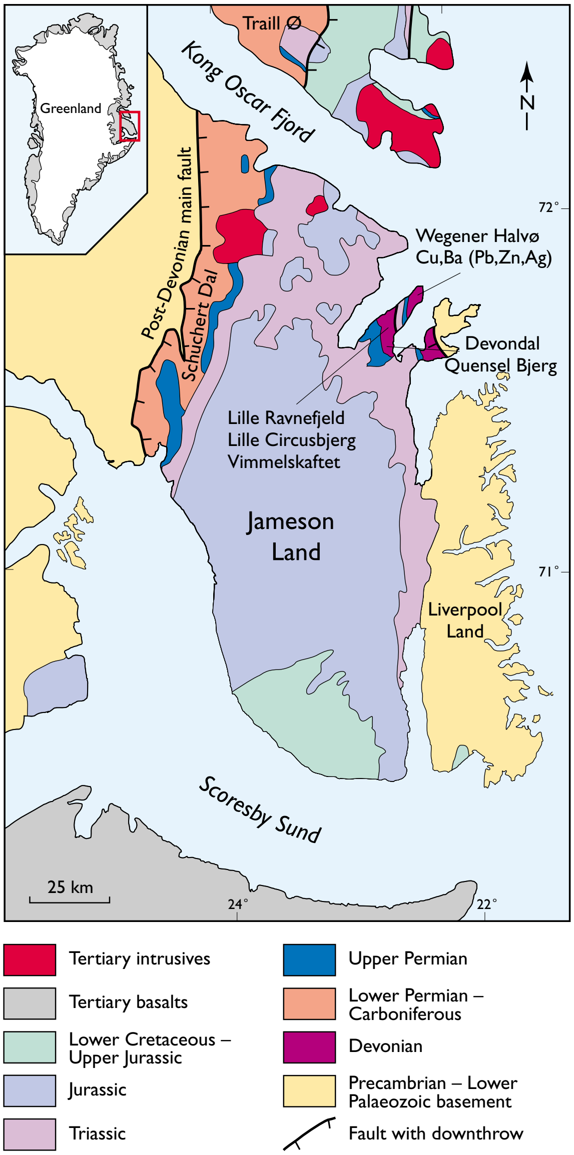


Fig. 1. Simplified geological map of the Jameson Land region in central East Greenland based on Survey maps.

Geology of Greenland Survey Bulletin 180, 81–87 (1998)

sulphides in the Wegener Halvø area (Fig. 1), may provide an important step in the evaluation of the presence or absence of early thermal activity on (or below) the Upper Permian sea floor.

Geology and mineralisation

The Ravnefjeld Formation forms part of the Upper Permian Foldvik Creek Group, which marks the first marine transgression in East Greenland since the Caledonian orogeny. The bituminous shales of the Ravnefjeld Formation are time equivalent with the carbonates of the Wegener Halvø Formation that forms reef structures along the eastern margin of the basin (Surlyk *et al.* 1986); the Ravnefjeld Formation partly interfingers with and partly overlies the reef structures on Wegener Halvø. The Ravnefjeld Formation is up to 60 m thick and can generally be divided into three bioturbated and two laminated units (Piasecki & Stemmerik 1991). Along the eastern basin margin, the formation is dominated by bituminous siltstones which in inter-reef depressions are interlayered with numerous packstone and grainstone layers; more sandy lithologies are found in some areas along the western basin margin.

Mineralisation with lead, zinc and copper sulphides in the Ravnefjeld Formation is so far only known from Wegener Halvø. The base metal enrichment in this area is, however, widespread and within an area of almost 50 km^2 ore minerals can be found at nearly all localities (Pedersen 1997). Base metal enrichment is present only in the lowermost few metres of the shale formation, except for a locality on Lille Ravnefjeld where abundant sphalerite and galena are found over a considerable vertical section. Heavily mineralised blocks in this area were first recorded in 1979 (Thomassen & Svensson 1980). Field work in 1996 (Pedersen 1997) confined the zone of strongest mineralisation to an inter-reef basin, coinciding with a N–S trending lineament. The lineament follows the southern continuation of the valley of Vimmelskaftet and is, hence, termed the Vimmelskaftet lineament. No vertical faulting is apparent along the lineament during or after the deposition of the shales, but the coincidence of the lineament with the axis of the shale basin both on Lille Ravnefjeld, and further south on Quensel Bjerg and in Devondal, suggests that it had acted as a zone of weakness already in Upper Permian time, leading to erosion during subaerial exposure of the carbonates prior to onset of shale deposition. The lineament is obvious in the field because it is intruded along its entire length by a Tertiary dolerite dyke. The intensity of mineralisation around the lineament, both in the shales on Lille Ravnefjeld and also in the carbonate reefs at Quensel Bjerg, suggests that the lineament has been an important zone of hydrothermal activity during one or more events (Pedersen 1997).

Morphology of primary pyrite

Primary sulphides have been examined in a drill core from the Schuchert Dal area in the western part of the basin where the shales are thermally immature and no signs of secondary metal enrichment exist. Pyrite is the main sulphide phase in this area. Based on analysis of the total sulphur, a higher degree of sulphidation is found in the two thick units of laminated organic-rich, calcareous shales, whereas a lower degree is found in the three thin bioturbated units (Piasecki & Stemmerik 1991). The sulphide phase consists of finely disseminated micrometre-sized grains within amorphous kerogen and can be divided into a number of morphotypes.

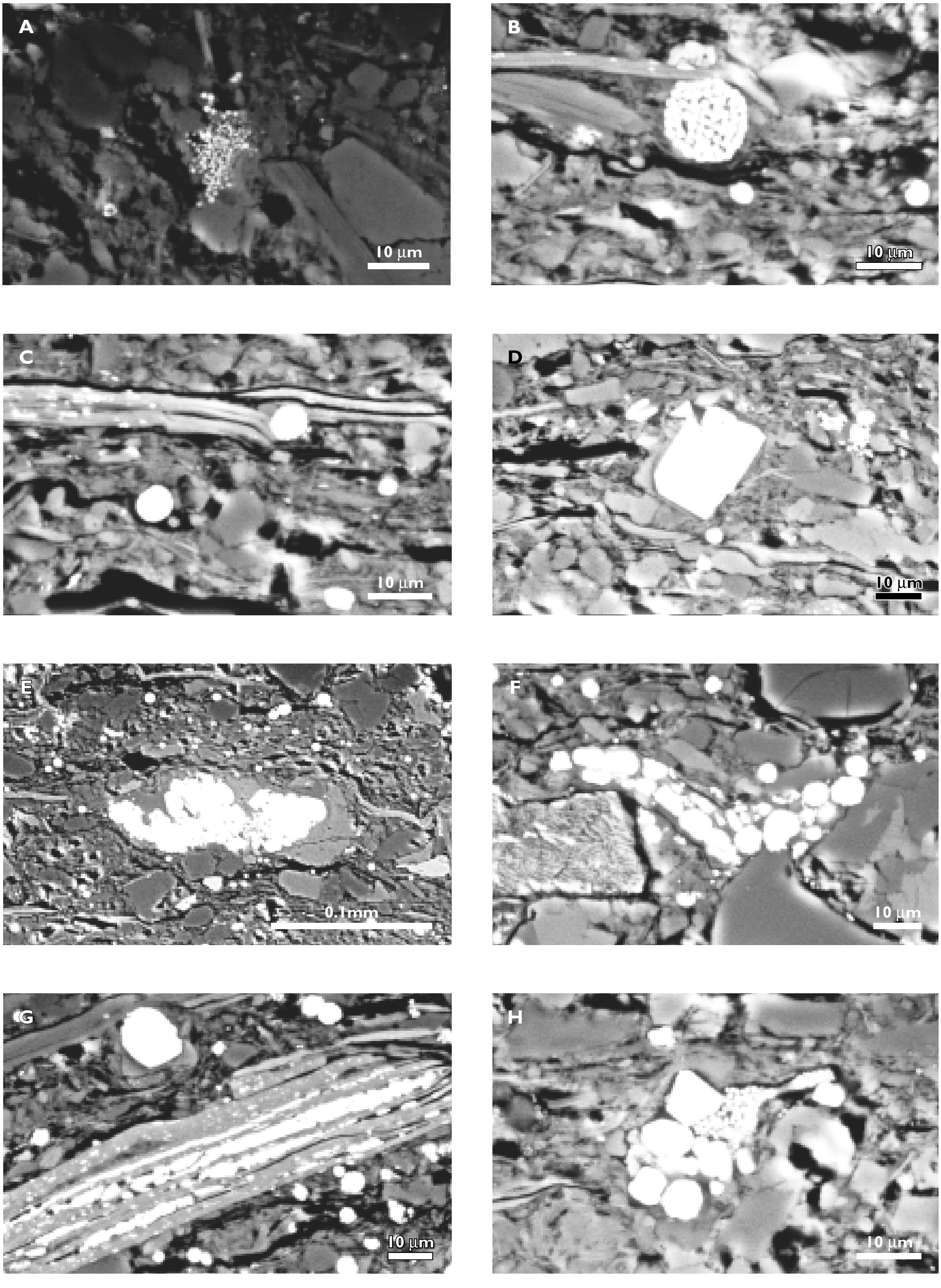
Clusters (up to 30 μm)

This morphotype is a non-spherical aggregate of euhedral to subhedral microcrystals. The microcrystals are normally arranged in a disordered way (Fig. 2A).

Framboids (up to 20 μm)

Two types of framboids have been recognised. One comprises anhedral grains, probably tiny framboids, and the other type consists of euhedral to subhedral grains. The grains in the two types are mostly arranged in a concentric pattern. The outer form of the framboids is always spherical.

Facing page:
Fig. 2. Backscatter photomicrographs showing the morphotypic features of primary diagenetic pyrite. Note the small scale. **A**: The cluster shown consists of tiny dispersed microcrystals. **B** and **C**: The end-members of a gradual transition from an ordinary framboid, via semi-massive to a totally massive morphotype. **D**: Large and well-organised cubic morphotype of smaller cubes. **E**: A concretionary outline of euhedral to subhedral pyrite surrounded by carbonate and quartz. **F**: Fragment of microfossil bryozoa which has become pyritised at apertures in the skeletal structure by anhedral to subhedral and massive framboidal pyrite. **G**: Pyritisation follows the layer structure of phyllosilicates. Note also the pyritisation and non-elastic property of pre-existing silicate minerals in (B) and (C). **H**: Combined type of cluster, massive framboids and euhedral grains have a nearly spherical outline.


A
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B
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C
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D
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E
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F
10 µm
G
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H
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The framboids and the above mentioned clusters can be found as ordinary (Fig. 2B) and semi-massive and massive (Fig. 2C) types occasionally with some overgrowth. These morphotypes mark the gradual transition from a cluster or framboid to a more massive form and finally to euhedral form. This is in good agreement with morphotypical and genetic models by Raiswell (1982) and Sawlowicz (1993).

Euhedral to subhedral (up to 500 µm)

Morphotypes of euhedral to subhedral cubes (few to tens of micrometres) are often found as individuals, some with remnant structures after clusters and framboids in their interior. Larger cubes may comprise a more composed and complex structure of numerous smaller cubes (Fig. 2D). Euhedral forms are also found in composite aggregates with an irregular and concretionary outline surrounded by large carbonate and quartz grains (Fig. 2E).

Anhedral (up to 100 µm)

In immature shales anhedral pyrite occurs as solitary and widely dispersed grains. These grains are often rich in inclusions. In some cases anhedral grains without larger inclusions occur as pyritic fill in fossils and replacing silicates (see below).

Pyritisation of fossils (up to 200 µm)

Pyritic fill is mainly found in apertures in fragmentary bryozoans (Fig. 2F); they are probably derived from time-equivalent bryozoan mounds of the Wegener Halvø Formation. Pyritisation of trace fossils has also been recognised in the bioturbated units of the Ravnefjeld Formation.

Sulphidation of silicates (up to 200 µm)

Subhedral to anhedral forms of pyrite have been observed in Fe-Ti-rich phyllosilicates (Fig. 2G). It is likely that the sulphidation has affected the interlayer cations between the layers in the phyllosilicate structure.

Combined forms (up to 200 µm)

Relatively large spherical to non-spherical aggregates of clusters, framboids and euhedral to anhedral grains have been found in small numbers (Fig. 2H). Clusters and framboids in this case can also be ordinary to massive. Up to a few hundred grains are estimated to construct the aggregates. The overall orientation of their two length-axes is parallel to the lamination of the calcareous shales.

The presence of these pyritic morphotypes indicates a very early sulphide formation by precipitation in a low-oxygen bottom water and porewater regime in a non-consolidated substrate (Canfield & Raiswell 1991). Certain morphotypes are preferentially found in the laminated units (clusters, framboids, pyritisation of fossils and sulphidation of silicates) and others in the bioturbated units (aggregates of euhedral-subhedral morphotypes). This distribution of the morphotypes could have been controlled by the properties of the substrate and its biological reworking, which also influenced the diffusion rates and availability of iron, sulphate and metabolic organic matter for bacterial sulphate reducers (BSR). Hydrogen sulphide produced by the BSR reacted with iron through monosulphide and polysulphide to form pyrite (Raiswell 1982). Preliminary S-isotope analysis supports the suggested formation pathway.

Morphology of base metal sulphides

Base metal sulphides in the mineralised horizons on Wegener Halvø mainly occur as disseminated, anhedral to subhedral grains or aggregates, varying in size from a few hundred micrometres to several centimetres. Continuous massive sulphide layers (2–3 cm in thickness) are found in the highly mineralised zone around the Vimmelskaftet lineament on Lille Ravnefjeld. Sulphide aggregates are occasionally monomineralic, but more often polymineralic assemblages are found.

Sphalerite and galena are by far the most abundant base metal sulphides in the Ravnefjeld Formation with chalcopyrite becoming increasingly important towards the north-west on Wegener Halvø. The base metal sulphides, in contrast to most pyrite, never show framboidal forms but always replace earlier minerals, sometimes with the original grain contours preserved as 'ghosts' in the sulphide grains.

Low-Fe calcite (commonly as shell fragments of smaller fossils) is the mineral that is most often replaced, but where the calcite is silicified, sulphides can replace both calcite and quartz with no tendency to favour either phase.

High-Fe calcite is not common in the samples studied, but where present usually occurs in association with base metal sulphides. Dolomite is a relatively com-

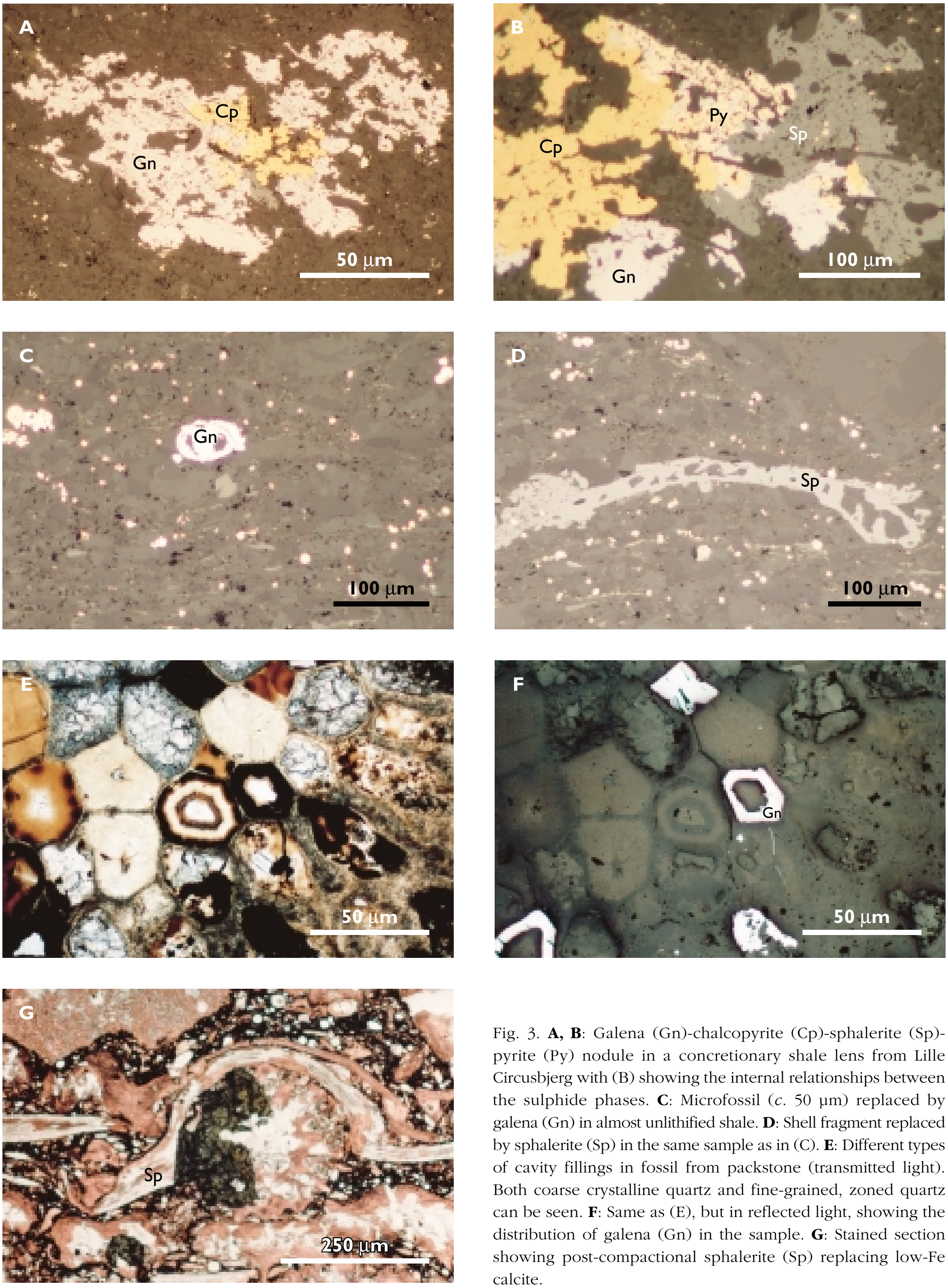

Fig. 3. **A, B**: Galena (Gn)-chalcopyrite (Cp)-sphalerite (Sp)-pyrite (Py) nodule in a concretionary shale lens from Lille Circusbjerg with (B) showing the internal relationships between the sulphide phases. **C**: Microfossil (*c.* 50 µm) replaced by galena (Gn) in almost unlithified shale. **D**: Shell fragment replaced by sphalerite (Sp) in the same sample as in (C). **E**: Different types of cavity fillings in fossil from packstone (transmitted light). Both coarse crystalline quartz and fine-grained, zoned quartz can be seen. **F**: Same as (E), but in reflected light, showing the distribution of galena (Gn) in the sample. **G**: Stained section showing post-compactional sphalerite (Sp) replacing low-Fe calcite.

mon phase in many mineralised samples, forming dispersed crystals which are obviously later than all other carbonates, although earlier than the introduction of base metal sulphides.

Base metal sulphides are always later than the diagnostic pyrite morphotypes, but have never been observed to replace them. Primary pyrite usually occurs in the organic-rich parts of the samples, whereas galena and sphalerite are concentrated in the carbonate-rich layers. In some cases, however, pyrite and base metal sulphides occur together, and sphalerite and galena can then be found to embrace framboids without imposing any effect on them. Occasionally, cubic pyrite crystals are found in zones of mineralisation. They may be either newly formed grains or derived by recrystallisation of framboidal pyrite during hydrothermal activity.

In general, four types of mineralised lithologies can be discerned (listed in order of importance):

1. Packstone layers;
2. Concretionary shale layers (cemented by calcite or quartz, or both);
3. Concretionary shale lenses (cemented by calcite);
4. Non-lithified shales.

The relative timing of mineral introduction into the sediments can be difficult to deduce. The discussion of primary or early diagenetic versus epigenetic mineralisation, however, can be eased if the sulphides can be related to a pre- or post-compactional stage. Composite nodules < 0.5 cm in size of galena, sphalerite, chalcopyrite and pyrite (Fig. 3A, B; in rare cases pure pyrite) are found finely disseminated throughout some concretionary lenses. Such shale lenses have obviously been cemented prior to compaction of the surrounding shales and can be assumed to have acted as impermeable lithologies into which post-compactional introduction of metals has been impeded. In some concretionary lenses, however, sulphides are clearly related to a few microscopic fractures (< 1 mm) from which metals can be seen to have diffused several centimetres into the surrounding rock.

In all the mineralised lithologies (except for the concretionary shale lenses), microfossils can be observed to be replaced by either galena (Fig. 3C) or sphalerite (Fig. 3D). In the mineralised packstone layers, all kinds of shell fragments, microfossils and cement can be replaced. Cavities within larger fossils may be filled with zoned quartz. The inner zone in some cavities consists of black quartz (Fig. 3E), the colour of which is assumed to stem from organic material. In these cases base metal sulphides have clearly crystallised after the quartz precipitation and have preferentially replaced the black quartz (Fig. 3F). The exact timing of this type of mineralisation is difficult to determine, but a relatively late period of mineralisation is indicated.

Only in a few cases is there evidence of clearly post-compactional crystallisation of base metal sulphides. One example is shown in Fig. 3G where a shell fragment can be seen to have bent around another fossil during compaction of the sediment. In this case, sphalerite has overprinted the compactional structures and is obviously post-compactional. This, however, is not certain evidence for late introduction of the metals into the sediments. The sphalerite could also be the result of recrystallisation of primary zinc-minerals during a thermal event, e.g. in the Tertiary.

It must be concluded that the timing and genesis of the base metal enrichment in the Ravnefjeld Formation on Wegener Halvø is still ambiguous and that further work is needed. We consider that sulphur isotope analysis of the various sulphides, and a detailed study of textures and geochemistry of the primary pyrite in the mineralised areas compared to unmineralised areas, may provide a way to determine the possible presence of an Upper Permian thermal event in the Wegener Halvø area.

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A reassessment of the timing of early Archaean crustal evolution in West Greenland

Stephen Moorbath and Balz Samuel Kamber

In last year's Review of Greenland activities, Kalsbeek (1997) divided the recent history of geochronology into three successive periods:

1. single-sample K-Ar and Rb-Sr mineral or whole-rock age determinations;
2. Rb-Sr and Pb/Pb whole-rock isochrons and multigrain zircon U-Pb isotope data;
3. the present, where 'single' zircon U-Pb data are predominantly used.

To these three, we would propose adding a fourth, namely a combination of all three, in order to achieve the maximum age information within complex terrains. For an early Precambrian terrain like that of West Greenland, we consider that the combined use of at least the last two approaches is essential (to which should be added the Sm-Nd method). In recent years, study of the geochronological evolution of the Godthåbsfjord and Isua regions has been dominated by rapid and precise ion-probe U-Pb dating of complex-structured zircons, and it has become fashionable to regard the wide range of zircon dates, and particularly the oldest, as giving the age of rock formation. Dates obtained from whole-rock Rb-Sr, Sm-Nd and Pb/Pb regressions have been regarded as too imprecise for adequate age resolution, whilst constraints on crustal evolution imposed by initial Sr, Nd and Pb isotope ratios have been summarily dismissed or totally ignored. We consider that this sole dependence on ion-probe dating of zircon can lead (as, indeed, in the early Archaean of West Greenland) to a potential misinterpretation of the timing of crustal evolution, especially in those cases where little or no information regarding the relationship between measured date and internal grain structure is available.

Figure 1 shows the localities mentioned in the text.

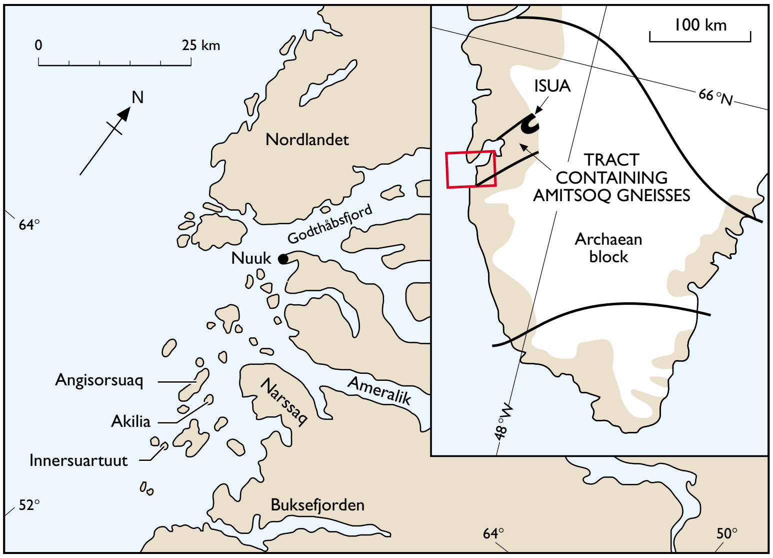
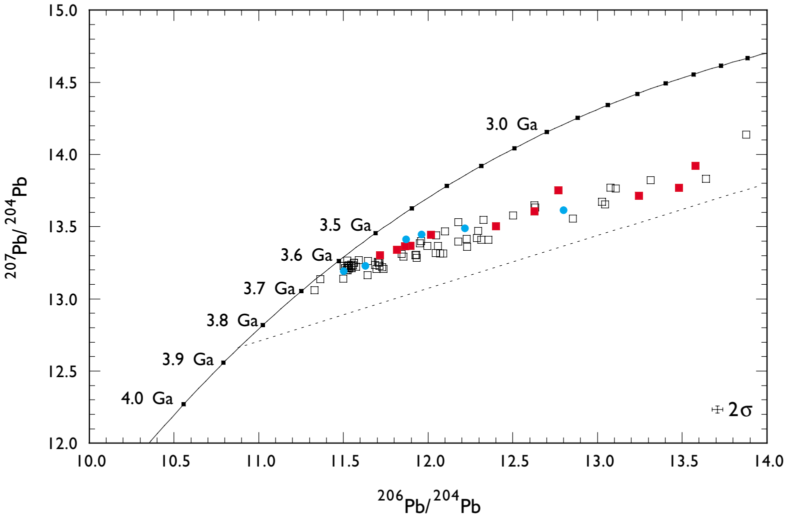


Fig. 1. Sketch-map of the area around Nuuk, West Greenland with localities mentioned in the text.

Fig. 2. Common Pb diagram with mantle evolution line after Kramers & Tolstikhin (1997). Black open squares represent 83 published whole-rock data points which regress to 3654 ± 73 Ma (MSWD = 17.6) and intersect the mantle evolution line at 3.66 Ga. Red full squares correspond to whole rock, HF-leached feldspar, and feldspar leachate analyses of four Amîtsoq gneisses claimed to have ages in the range 3.82–3.87 Ga from U-Pb zircon dates (for sampling details see text). Mantle-derived Pb of 3.85 Ga (stippled line) would be expected to lie on a quasi-parallel trend to the bulk Amîtsoq data, but off-set down towards older model intersection ages. Blue full circles are leached plagioclase and whole rock data from gabbroic Akilia Association enclaves. Some of these enclaves are cut by gneiss sheets for which ages of 3.85–3.87 Ga have been claimed. Their Pb isotope composition offers no evidence for such an old age but is compatible with a 3.67 Ga Sm-Nd isochron age (Fig. 3) obtained on similar samples.



Whole-rock regression ages for the Amîtsoq gneisses

We have regressed all available whole-rock isotopic data for the Amîtsoq gneisses (source references available from the authors), to yield concordant Rb-Sr (3660 ± 67 Ma), Sm-Nd (3640 ± 120 Ma), and Pb/Pb (3654 ± 73 Ma) ages. These regressions are by no means perfect isochrons, and the scatter of points about the regressions in excess of analytical error is due to: (1) open-system behaviour for parent or daughter isotopes, or both, during well-attested late Archaean and mid-Proterozoic metamorphism; (2) a small degree of heterogeneity in initial Sr, Nd and Pb isotope ratios for different components of the Amîtsoq gneisses; (3) a combination of these. However, we regard the weighted mean age of 3655 ± 45 Ma (2 sigma error) from all three methods as a reliable estimate for the emplacement age of the magmatic precursors of the Amîtsoq orthogneisses. It is improbable that agreement between these three methods is simply fortuitous, or the result of some massive, regional metamorphic or metasomatic event. Furthermore the initial Sr, Nd and Pb isotopic constraints are also concordant, all strongly indicating a mantle-like source, rather than much older, reworked sialic crust.

All Amîtsoq gneisses studied by the ion-probe U-Pb technique have yielded at least some zircon dates in this range, and *c.* 3.65 Ga is seen as the age of a major crust-forming event by Nutman *et al.* (1993, 1996). However, these workers have also reported many older zircon dates from which it is concluded that the gneiss complex had a complicated earlier history, having been added to, and modified, in several events starting at *c.* 3900 Ma and extending down to *c.* 3600 Ma. Fortunately, it is possible to test these claims independently by combining information obtained by ion-probe U-Pb dating and Pb-isotope systematics (the combined approach 4). Of particular interest is the question of whether the zircon dates really refer to the true age of formation of their host rock, or whether they only refer to the age of the zircon itself. In the latter case, it would have to be concluded that the zircon is inherited from an older rock which may no longer be exposed. Zircon is known to be an extremely hardy, resistant mineral which can survive sedimentary and magmatic cycles (e.g. Lee *et al.* 1997; Mezger & Krogstad 1997).

Pb-isotopic constraints for the age of the Amîtsoq gneisses

The evolution of Pb isotopes in continental crust, oceanic crust, mantle and meteorites through earth's history has been closely studied for over forty years. Part of the primary isotopic growth curve for mantle Pb, which links the most primitive Pb of iron meteorites with modern mantle-derived Pb, is shown in Figure 2. The shape of this curve, as well as the increasing resolution towards older ages, is due to the very different half-lives of ^{235}U (703.8 Ma) and ^{238}U (4468 Ma). Here we use the mantle evolution curve of Kramers & Tolstikhin (1997), which barely differs in the relevant time range from the well-known primary growth curve of Stacey & Kramers (1975). It should be noted that the $^{207}Pb/^{206}Pb$ compositions of 3.85 Ga and 3.65 Ga-old mantle Pb differ by 13%, far outside any analytical uncertainties (typically *c.* 0.15%).

All 83 Amîtsoq gneiss common leads so far analysed by various workers fall within the data envelope shown in Figure 2. The data points scatter around a regression line which yields an age of 3654 ± 73 Ma. Most present-day Amîtsoq gneiss leads are extremely unradiogenic (because of the low U/Pb ratio of the gneisses), and fall between 11.5 and 12.5 on the $^{206}Pb/^{204}Pb$ scale (Fig. 2). This is the main reason for the fairly high age error on the regression line. Of much greater, indeed crucial, importance is that the Amîtsoq gneiss Pb-isotope regression intersects the mantle evolution curve precisely at 3.66 Ga. This is, within error, identical to the 3.65 Ga intercept with the earlier growth curve of Stacey & Kramers (1975). From this we conclude that the magmatic precursors of all the analysed Amîtsoq gneisses were derived from the mantle, or from a geochemically similar source, at 3.65–3.66 Ga, after which they became part of the continental, granitoid crust. There is simply no hint of the presence of any Amîtsoq gneiss which began its existence in the crust as long ago as *c.* 3.85 Ga (Fig. 2).

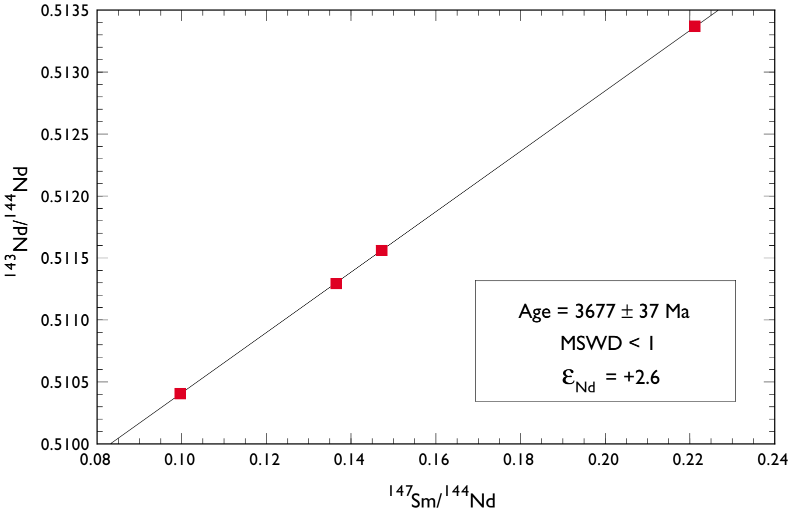
It might be argued that all of the above gneisses would yield ion-probe U-Pb zircon dates of *c.* 3.65 Ga. Unfortunately, few such comparisons are available. We have therefore included in our common Pb isotopic studies several Amîtsoq gneisses which yield much older ion-probe zircon dates as far back as *c.* 3870 Ma, for each of which the oldest measured ion-probe date is interpreted as the true age of rock formation (e.g. Nutman *et al.* 1997a). Of particular interest are Amîtsoq gneisses in and around the island of Akilia, about 25 km south of Nuuk, where ion-probe dates in the range of 3872–3619 Ma have been reported within a small area (Nutman *et al.* 1996, fig 2.). On Akilia itself, discordant sheets of Amîtsoq gneiss with the oldest ion-probe dates of 3860–3870 Ma cut metasedimentary and meta-igneous rocks of the so-called Akilia Association, which are thus regarded as even older (Nutman *et al.* 1997a). Here an enclave of highly metamorphosed banded iron formation contains accessory apatite with graphite inclusions yielding a C-isotope signature regarded as biogenic in origin (Mojzsis *et al.* 1996). Consequently, Nutman *et al.* (1997a) claim that life existed on earth prior to 3860 Ma, and might therefore have overlapped with a time when the earth was still being affected by major impacts, such as probably terminated on the moon at *c.* 3.80 Ga. Overlap of truly major impacts with the existence, or origin, of life is regarded as highly improbable (e.g. Maher & Stevenson 1988; Sleep *et al.* 1989). This is further discussed below.

Pb-isotopic compositions have been measured on whole rocks and feldspars for the following samples with ion-probe U-Pb zircon dates $\gg$3650 Ma: (1) discordant sheets of Amîtsoq gneiss on Akilia, as described above, (2) an Amîtsoq gneiss (GGU 110999) from the island of Angisorsuaq, 2 km west of Akilia, which has been much analysed for 25 years, and which was the first such sample to give an 'old' ion-probe date of 3820 Ma (Kinny 1986), (3) gabbroic Akilia Association enclaves from Akilia and the nearby (10 km to the south) island of Innersuartuut, which are older than the discordant Amîtsoq gneiss sheets with their respective ion-probe zircon dates of 3865 Ma (Nutman *et al.* 1997a) and 3784 Ma (Bennett *et al.* 1993).

Figure 2 shows that the Pb-isotopic compositions of all these samples fall exactly on the regional Amîtsoq field which regresses at 3654 ± 73 Ma and, much more significantly, intersects the mantle evolution curve at 3.65 to 3.66 Ga. We conclude that the magmatic precursors of even those Amîtsoq gneisses which yield ion-probe U-Pb zircon dates $\gg$3650 Ma are the products of a major mantle-crust differentiation episode at around 3.65 Ga (e.g. Moorbath & Taylor 1981). There is no sign from the Pb isotopes that crustal development of any of these Amîtsoq gneisses or gabbroic Akilia enclaves began as early as the times given by the ion-probe dates (Fig. 2).

The inescapable corollary from these results is that zircons significantly older than *c.* 3.65 Ga are inherited grains from some older, evolved, regional crust of as yet unspecified type, which may no longer be exposed. Our analysis of all published ion-probe data (Kamber & Moorbath 1998), together with recent ion-probe data

Fig. 3. Sm-Nd isochron plot for data of Bennett *et al.* (1993) on Akilia Association enclaves from the island of Akilia (one sample – the highest point), and the nearby island of Innersuartuut (three samples). The mean square weighted deviate (MSWD) of < 1 shows that this is a statistically perfect isochron. ε_{Nd} is a measure of the initial $^{143}Nd/^{144}Nd$ ratio, which is of great importance for petrogenetic and geochemical studies as well as for modelling mantle evolution. The quoted error on the age is 2 sigma (95% confidence level).



(Nutman *et al.* 1997b) on detrital zircons from a metaquartzite in the Isua supracrustal belt, some 150 km north-east of Nuuk, suggests that an event at *c.* 3.85 Ga is of particular regional importance. Thus, whilst the discovery of ≫3650 Ma-old zircons with the ion-probe has been of great importance, we consider that they do not date the time of formation of the rocks which presently host them. The geochemical nature of the *c.* 3.85 Ga-old source rocks is difficult to constrain. Contamination of the younger melts with older material (i.e. the source-rocks of the *c.* 3.85 Ga-old zircons) had minimal effects on the Pb-, Nd-, and Sr-isotope systematics (although some of the scatter around the regressions might perhaps be explained as stemming from very minor contamination with country-rock). Detailed multidisciplinary work on the ancient zircons themselves will hopefully elucidate the nature of their source rocks.

Significance for age of earliest life

Our re-interpretation of a rock formation age of *c.* 3.65 Ga for discordant Amîtsoq gneiss sheets on Akilia provides a new, less spectacular, minimum age for those Akilia Association enclaves which bear C-isotope evidence for possibly biogenic processes (Mojzsis *et al.* 1996). The fact that Akilia Association enclaves from Akilia and Innersuartuut fall on an indistinguishable Pb-isotopic trend from the discordant (and other) Amîtsoq gneisses means that the enclaves cannot be more than a few tens of millions of years older than the gneisses (provided they were derived from a mantle-like source, which seems likely given their gabbroic composition and association with ultramafic rocks). There is some published, independent evidence for this, which we now discuss briefly.

Bennett *et al.* (1993) reported Sm-Nd data for a suite of gabbroic enclaves of the Akilia Association, including Akilia and Innersuartuut. Using minimum age constraints obtained from ion-probe U-Pb zircon data in the range of 3872 to 3784 Ma from discordant and enclosing Amîtsoq gneisses (see above), they calculated initial Nd isotope ratios for the Akilia gabbros and, together with analogous comparative data for the Amîtsoq gneisses, arrived at a model of major Nd-isotope heterogeneity in the earth's mantle in early Archaean times. This approach, which has been strongly criticised by Moorbath *et al.* (1997), assumes that every analysed rock remained a closed system to Sm or Nd diffusion since the time given by the U-Pb zircon date. But were the bulk rocks already in existence at the time given by the U-Pb zircon dates? If one plots the Sm-Nd data of Bennett *et al.* (1993) for five separate localities (seven data points) of Akilia Association gabbroic enclaves, they yield an isochron age of 3675 ± 48 Ma. Plotting only the data from Akilia (one sample) and Innersuartuut (3 samples) yields a perfect Sm-Nd isochron (MSWD < 1) with an age of 3677 ± 37 Ma, as shown in Figure 3. It is probable that this is a close estimate for the age of not only the gabbroic enclaves on these islands, but also for the closely associated banded iron formation lithologies which (on Akilia) contain apatite with graphite inclusions of probable biogenic origin (Mojzsis *et al.* 1996). It should be remembered that on Akilia, the Akilia Association enclaves are cut by a gneissic granitoid sheet which yields zircon U-Pb dates up to 3870 Ma, which we regard as inherited zircons from a time when the present host rocks did not even exist.

The only ion-probe zircon U-Pb date so far measured directly on an Akilia Association rock, namely a schist from Innersuartuut, was reported by Schiøtte & Compston (1990). They obtained a complex age pattern, but favoured 3685 ± 8 Ma as representing the original age of this part of the Akilia Association and found no zircons approaching the value of *c.* 3865 Ma obtained by Nutman *et al.* (1997a) for the discordant gneiss sheets on Akilia.

Direct age constraints on the Akilia Association obtained with three independent methods thus yield a concordant deposition age: (1) Pb/Pb model age constraints on gabbroic samples indicate a mantle extraction age between 3.70 and 3.65 Ga; (2) Sm-Nd analyses of similar gabbroic samples yield an isochron age of 3677 ± 37 Ma, and (3) a volcanogenic Akilia Association schist was dated at 3685 ± 8 Ma with the U-Pb ion-probe method. The combined age of *c.* 3.67–3.68 Ga is in direct conflict with the interpretation of U-Pb zircon age spectra of younger, cross-cutting gneiss sheets, which were believed to be as old as 3.87 Ga (Nutman *et al.* 1997a). However, a closer inspection of the age spectra, in other words the data themselves, reveals that an alternative interpretation is equally plausible. The ion-probe U-Pb zircon age spectra of all three analysed discordant gneiss sheets can be statistically analysed to yield between two and four age populations per spectrum (Nutman *et al.* 1997a, table 3). No matter which analysis is preferred, prominent, co-existing age populations are always found in the range of 3.81–3.86 Ga and 3.60–3.65 Ga. Whilst Nutman *et al.* (1997a) prefer to view the older population as representing the rock formation age, the combined geochronological evidence in fact clearly shows that the younger 3.60–3.65 Ga population corresponds to the rock formation age and that the 3.81–3.86 Ga population was inherited. Our re-interpretation is not only compatible with the direct age constraints on Akilia Association rocks but also with the aforementioned Pb isotope characteristics of the cross-cutting Amîtsoq gneiss sheets, thereby demonstrating that the most reliable age constraints in complex gneiss terrains are obtained by a combination of geochronological techniques, rather than by application of only one (the most precise) geochronometer.

The revised dates presented here for Akilia Association enclaves of possible significance for the study of earliest life are nearly 200 Ma younger than the minimum date of *c.* 3865 Ma proposed by Nutman *et al.* (1997a). If our re-interpretation is correct, the question of overlap of earliest life with a lunar-type impact scenario terminating at *c.* 3.80 Ga, as suggested by Nutman *et al.* (1997a), becomes irrelevant.

Space limitations do not allow discussion here of the age of the Isua greenstone belt. However, we agree with Nutman *et al.* (1997b) that deposition of the major part of the belt probably occurred at *c.* 3.71 Ga.

This paper summarises a major conflict between current interpretations of the geochronological evolution of the early Archaean complex of the Godthåbsfjord region of West Greenland. We trust that future work, combining approaches (2) and (3) of Kalsbeek (1997), will resolve this controversy.

Acknowledgements

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Early Archaean Isua supracrustal belt, West Greenland: pilot study of the Isua Multidisciplinary Research Project

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The Isua belt of 3.8–3.7 Ga metavolcanic and metasedimentary rocks, is located 150 km north-east of Nuuk, within the Archaean gneiss complex of West Greenland. Most of this gneiss complex consists of late Archaean rocks with a minor component of early Archaean age, including the oldest known supracrustal rocks on Earth. The Isua belt contains the best preserved of the oldest supracrustal components and is therefore of vital importance in providing information on the oldest known terrestrial environments and a prospective locality in which to search for the earliest traces of life on Earth (Mojzsis *et al.* 1996). The Isua Multidisciplinary Research Project (IMRP) aims to coordinate a reinvestigation of the geology of the Isua belt and adjacent tonalitic gneisses with a broad-based, diversely skilled, international research team. IMRP is supported by the Danish Natural Science Research Council, the Commission for Scientific Research in Greenland and the Minerals Office of the Greenland Government (from 1998, the Bureau of Minerals and Petroleum).

The project began in 1997 with a pilot study of the north-east sector of the Isua belt to test the feasibility of reinvestigating the early Archaean geology on the basis of new mapping. Five weeks of field work were carried out by a core of four geologists (P.W.U.A, C.M.F., S.M., J.S.M.) augmented by visits of shorter duration by G. Arrhenius, A. Hofmann, V.R. McGregor, S. Mojzsis, R.K. O'Nions and H.K. Schønwandt. This report outlines the geological background to the current study and the results of the 1997 pilot project.

Previous work

The region was first explored geologically by the Kryolitselskabet Øresund A/S during the 1960s (Keto 1998) who discovered the Isua belt of metavolcanic and metasedimentary rocks, including the major banded iron formation at Isukasia. This company made the first geological map of the region and drilled the iron formation.

The great antiquity of these rocks was first established by Moorbath *et al.* (1972, 1973) who obtained a Pb/Pb whole-rock age of 3710 ± 70 Ma on the iron formation at Isukasia, and a Rb/Sr whole-rock age of 3700 ± 140 Ma from the adjacent tonalitic gneiss. The main features of the Precambrian geology were first described by Bridgwater & McGregor (1974) on the basis of 14 days reconnaissance. They compared the tonalitic gneiss to the Amîtsoq gneiss of the Godthåb (Nuuk) region, and the dykes that cut both the gneiss and the supracrustal rocks to Ameralik dykes. They surmised that some quartzofeldspathic and ultramafic units could have been derived from volcanic rocks, and they recognised a distinctive conglomeratic unit that they traced for over 14 km along strike. Near the lake 678 (Fig. 1) the conglomeratic unit was found to comprise deformed "cobs and boulders ranging from a few centimetres to 2 metres in diameter, set in a fine-grained, carbonate-bearing matrix" (Bridgwater & McGregor 1974, p. 51). This was the first discovery of deformed primary depositional features in the Isua belt. A search was made, both in the field and amongst the samples collected, for granitic fragments that could have been derived from an older basement. Analyses of samples indicated that both the clasts and the matrix had a similar granitic composition. Ignimbritic textures were discovered in some of the least deformed fine-grained matrix (D. Bridgwater, personal communication 1975) and it was concluded that this unit was derived from acid volcanic and volcanogenic sedimentary rocks. Geochemical and isotopic studies of both the clasts and matrix confirmed that both had similar REE compositions and ages (Moorbath *et al.* 1975). U-Pb analyses of single zircons from acid volcanic clasts gave a more precise age of $3770\,^{+0.012}_{-0.009}$ Ga, the oldest age then reported from any terrestrial rock (Michard-Vitrac *et al.* 1977). The 1975 statement by Moorbath *et al.* (p. 238) that "the Isua supracrustal succession is thus at present the oldest dated greenstone belt on the earth" is still valid in 1998.

The supracrustal rocks were mapped by J. H. Allaart in 1974–75 for the Geological Survey of Greenland (GGU, now incorporated in the Geological Survey of Denmark and Greenland, GEUS). Allaart delineated the extent of the major belt of metasedimentary and meta-igneous rocks, and presented an outline of the geology (Allaart 1976). He discussed various interpretations of the quartzofeldspathic schists with quartzofeldspathic fragments and concluded that they were derived from acid volcanic rocks. The geology was also described and interpreted by Bridgwater *et al.* (1976) in the context of the regional geology of the Godthåbsfjord region. Both Allaart (1976) and Bridgwater *et al.* (1976) suggested that the Isua belt of supracrustal rocks was probably a fragment of a more extensive sequence, and Bridgwater *et al.* (1976) noted the similarity with younger greenstone belts. The contacts of the Isua supracrustal rocks with the adjacent tonalitic gneisses are strongly deformed, but all these authors considered that the tonalitic gneisses were younger than the supracrustal rocks.

There was a surge of research activity during the late 1970s to early 1980s on a variety of topics including: stratigraphy and sedimentology (Dimroth 1982; Nutman *et al.* 1984); structure (James 1976); petrology, mineralogy and geochemistry (Appel & Jagoutz 1978; Appel 1979a, b, 1980; Schidlowski *et al.* 1979; Gill *et al.* 1981; Boak *et al.* 1983); metamorphism (Boak & Dymek 1982); geochronology (Moorbath *et al.* 1975; Baadsgaard 1976; Michard-Vitrac *et al.* 1977; Hamilton *et al.* 1978), lead, sulphur and oxygen isotope studies (Oskvarek & Perry 1976; Oehler & Smith 1977; Perry & Ahmad 1977; Appel *et al.* 1978; Monster *et al.* 1979), and organic chemistry (Nagy *et al.* 1975, 1977). The Isua belt was remapped by A.P. Nutman in 1980–82 at a scale of 1:10 000, and the mapping was extended across the adjacent gneisses. This work was published with more detailed accounts of the supracrustal rocks by Nutman *et al.* (1983) and Nutman (1986).

Subsequent work at Isua has been carried out intermittently by three independent groups: D. Bridgwater, M.T. Rosing and colleagues at the Geological Museum in Copenhagen; P.W.U. Appel (GEUS), S. Moorbath (Oxford University) and colleagues; and A.P. Nutman (Australian National University) and C.R.L. Friend (Oxford Brookes University). These studies have led to overviews by Nutman *et al.* (1997), a reinterpretation of the metacarbonate rocks (Rose *et al.* 1996), and a substantial reappraisal of the Isua supracrustal belt by Rosing *et al.* (1996). Economic interest in the area was renewed in the 1990s with drilling of the iron formation by Rio Tinto Ltd., and prospecting for gold and base metals by Nunaoil A/S.

Isua Multidisciplinary Research Project

Aims

The Isua Multidisciplinary Research Project (IMRP) aims to provide a new phase of broadly-based, detailed field and laboratory research on the Isua supracrustal belt, based on new detailed mapping of the whole belt and adjacent gneisses. A major aim of the project is to determine the surface conditions on the Earth and the main geological processes current between *c.* 3800 and 3700 Ma. The project includes a search for some of the oldest traces of life on Earth by Stephen Mojzsis, and the broad multidisciplinary nature of the new project, building on previous studies, provides a firmer foundation for this kind of study than did its predecessors.

Achievements of 1997 pilot project

The pilot study involved preliminary remapping of the north-eastern part of the Isua belt at a scale of 1:20 000, and concurrent detailed studies of some of the metasedimentary rocks. The region was found to comprise three fault-bounded tectonic domains (Fig. 1). Two of these domains (NW and SE) consist of intensely deformed schists, whereas strain was relatively low throughout a central domain (CD) in which primary volcanic features are relatively well preserved. This central zone largely consists of metamorphosed and moderately deformed basaltic pillow lavas, pillow breccias, and heterogeneous volcanic breccias, interbedded with minor metamorphosed chert and conglomerate, and a major unit of banded iron formation. These rocks are described in detail by Appel *et al.* (1998), and are here only illustrated by photographs of typical examples (Figs 2–6). The discovery and delineation of this fault-bounded zone of relatively low total strain (Fig. 1, domain CD) was the most significant achievement of the 1997 pilot project, and has important regional implications. This low strain domain (CD) provides the best, and largest known, region in which to investigate the oldest known surface environments on Earth, as well as the geochemistry of contemporaneous basaltic magmas. The rocks in this domain make up a relatively intact stratigraphic sequence that is probably one of the best preserved, oldest terrestrial stratigraphic records.

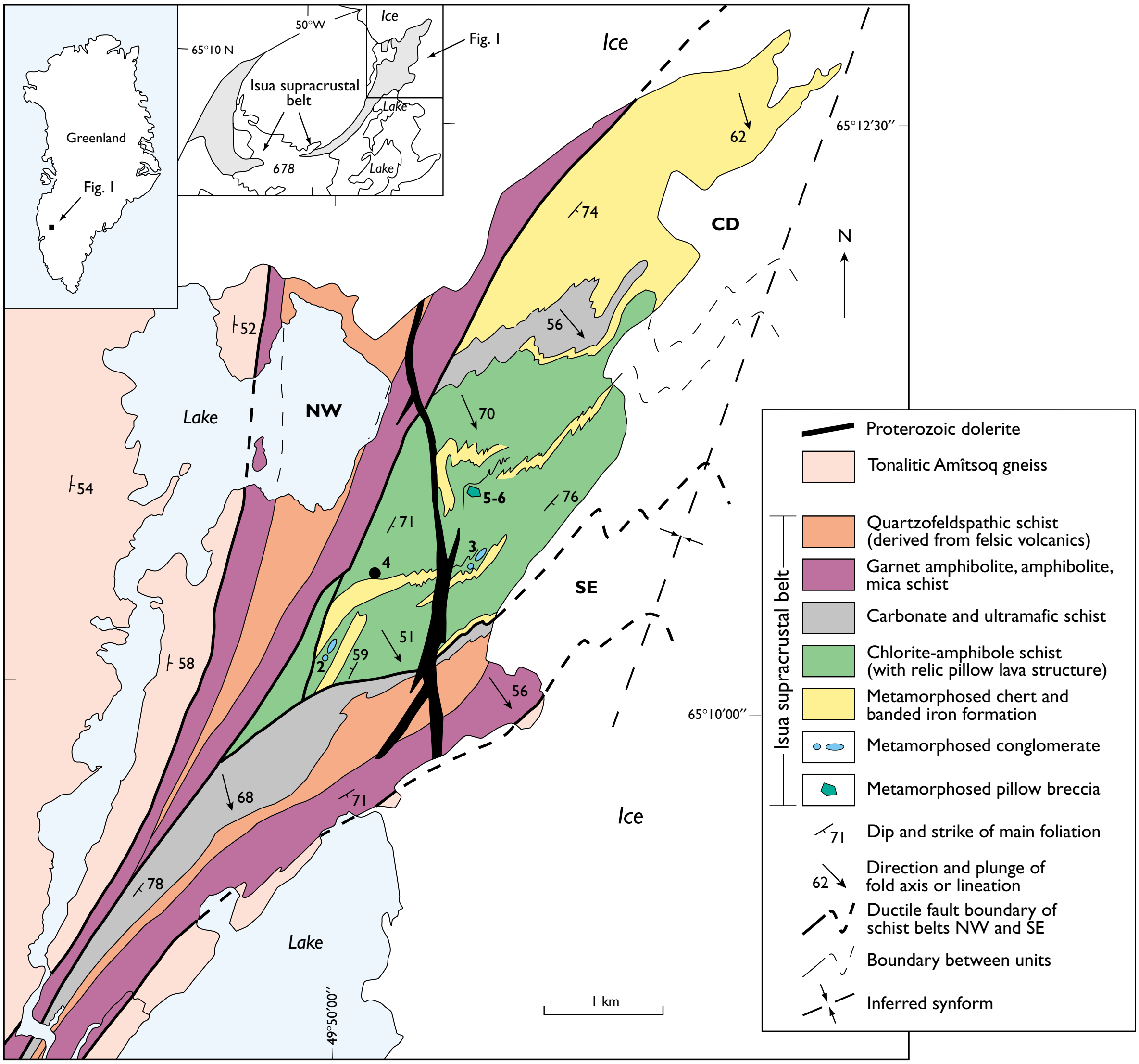

Fig. 1. Simplified geological map of the north-eastern part of the Isua supracrustal belt. Arrows show the direction and plunge of fold axes and lineations related to the major synform. Dips and strikes relate to the main schistosity folded by the major synform. The letters NW, CD and SE indicate the north-west, central and south-east tectonic domains respectively. Numbers 2 to 6 locate outcrops shown on Figures 2 to 6. The dashed boundaries over the ice are postulated from the structure of the adjacent rock outcrops.

The sequence largely consists of basaltic pillow lava and associated breccias, interbedded with chert and banded iron formation. All the other components of the Isua belt in the region studied are intensely deformed schists in which primary statigraphy has been severely modified, and almost obliterated, by tectonic transposition. Elsewhere in the Isua belt primary depositional features have only been found locally in very small areas of relatively low strain in generally schistose units derived from acid volcanic and volcanoclastic sedimentary rocks, such as the locality discovered by Bridgwater & McGregor (1974). Pillow lava structures have not been described before, although they have been mentioned from two localities (within the newly-mapped domain CD) by Allaart (1976), Komiya & Maruyama (1995) and Nutman *et. al.* (1996), and as personal communication from L. Keto (1975).

The main stratigraphic unit of pillow lava extends over an area of 6 km^2 in the central domain (Fig. 1). This rock was previously mapped as 'garbenschiefer amphibolite', a unit that was traced along the whole length of the Isua belt and which formed the largest single component (25%) of the belt (Nutman 1986). This 'garbenschiefer unit' was interpreted as a "gabbroic, possibly sill-like intrusion(s)" by Nutman (1986, p. 15; 1997). However, Rosing *et al.* (1996, p. 43) referred to "sedimentary units with well-preserved Bouma sequence structures that are interbedded with, and grade into, garbenschiefer-textured magnesian schists", and suggested that the 'garbenschiefer unit' was derived from a volcano-sedimentary pile rather than an intrusion. The new field work supports the interpretation of Rosing *et al.* (1996). We found that in the north-eastern part of the Isua belt the so called 'garbenschiefer unit' was predominantly derived from basaltic pillow lava and, although thoroughly recrystallised, still largely preserves deformed pillow lava structure. A brief reconnaissance of a section across the thickest part of the 'garbenschiefer unit' to the west of lake 'Imarsuaq' found that this section also mainly consists of deformed pillow lava, and this may be the dominant protolith. The geochemistry of the 'garbenschiefer unit' was discussed by Gill *et al.* (1981) who showed that the composition of the samples they studied was generally that of high-Mg basalt, rich in Al_2O_3 (15–20%) and low in CaO (8–19%).

The new work of 1997 supports previous suggestions (such as Bridgwater *et al.* 1976, p. 24) that "the original stratigraphy has been disturbed by thrusting", and that the Isua belt may comprise a number of tectonic slices rather than a single stratigraphic sequence or 'coherent stratigraphy' as described by Nutman (1984). However, the new mapping of 1997 does not substantiate the location of major 'tectonic breaks' described by Nutman (1997) and Nutman *et al.* (1997).

In 1986 Nutman proposed that the Isua belt could be divided into two stratigraphic sequences that he called A and B, separated by a fault, and each sequence was divided into a number of formations. Nutman *et al.* (1997) determined different U-Pb SHRIMP ages of zircons from rocks of similar appearance and acid volcanic or volcaniclastic origin in the two sequences. The sample from sequence B gave an age of *c.* 3710 Ma whereas a sample from sequence A gave an age of > 3790 Ma. On this basis Nutman *et al.* (1997, p. 271) concluded that 'sequences A and B' represented "unrelated supracrustal packages of different ages (> 3790 Ma and ~ 3710 Ma), that were juxtaposed in the early Archaean". The dated sample from 'sequence B' came from within the unit of quartzofeldspathic schist in the north-west domain (NW in Fig. 1). The sample from 'sequence A' came from a unit of similar quartzofeldspathic schist at a locality

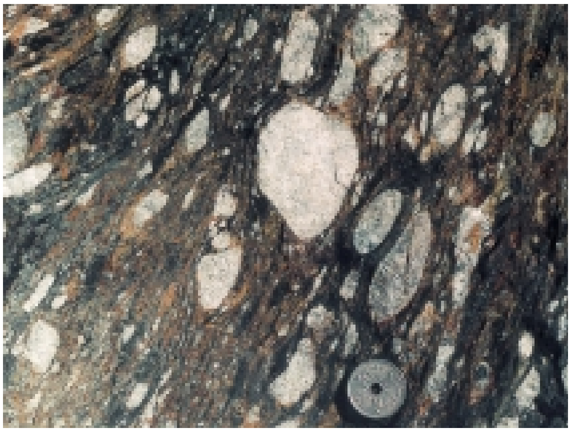

Fig. 2. Metaconglomerate with quartz pebbles of diverse size in a siliceous schistose matrix. All rocks shown in Figures 2–6 are deformed and are viewed perpendicular to the stretching lineation. The coin is 2.5 cm in diameter.

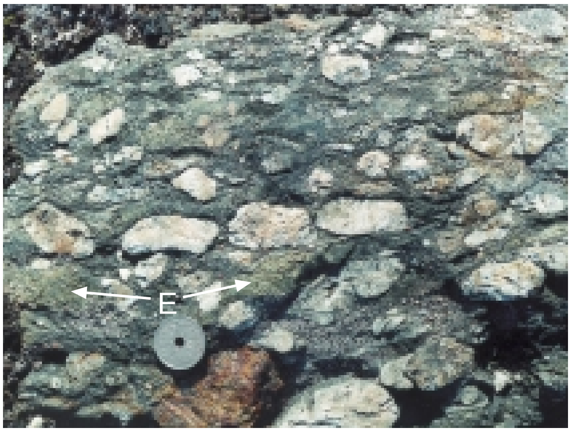

Fig. 3. Polymictic metaconglomerate with pebbles of quartz and quartz-epidote (E).

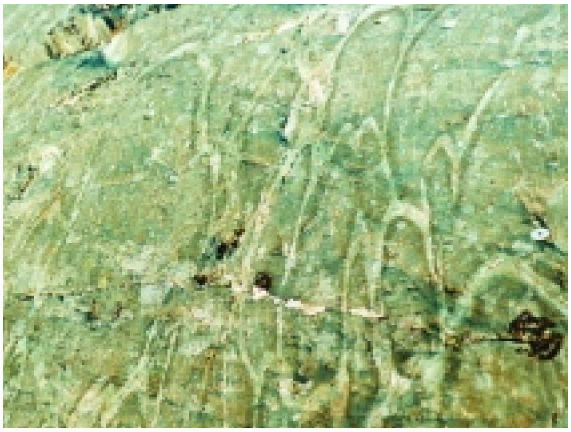

Fig. 4. Metabasalt pillow lavas with dark rims, in a matrix of chert.

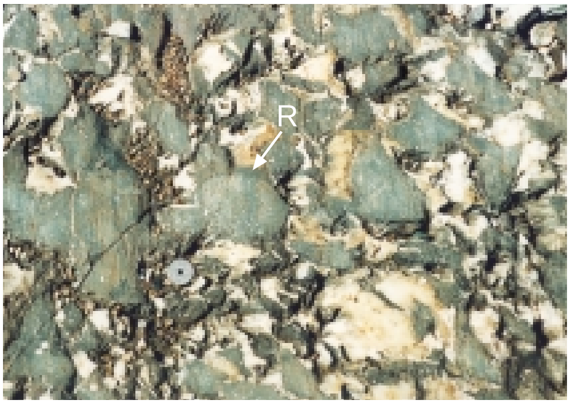

Fig. 5. Recrystallised pillow breccia with angular fragments of amygdaloidal pillow basalt in a matrix of chert. The arrow (R) points to a fine-grained pillow rim.

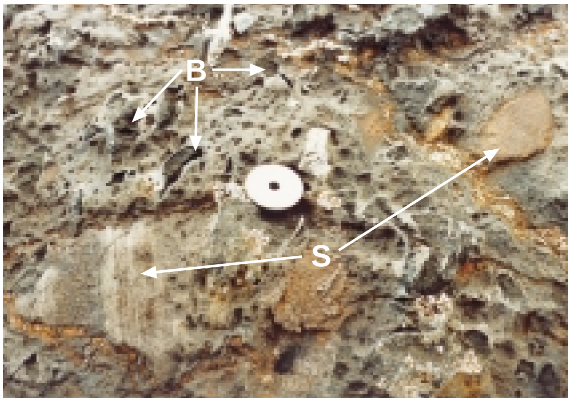

Fig. 6. Recrystallised volcanic breccia with fragments of metamorphosed amygdaloidal basalt (B) and volcanogenic sedimentary rocks (S).

7 km along strike to the south-west of the south-east domain (SE in Fig. 1). However the tectonic contacts shown by Nutman (1986, 1997) and Nutman *et al.* (1997) between 'sequences A and B' do not match the tectonic boundaries between the three tectonic domains (NW, CD, SE) shown on Figure 1. Nutman (1997) describes the fault between 'sequences A and B' as a 'Proterozoic reverse fault', but neither this nor the location of 'early Archaean tectonic breaks' shown on his map in the north-east part of the Isua belt were substantiated by the new mapping in 1997, and none of these faults coincide with the boundaries of the tectonic domains shown on Figure 1.

Acknowledgements

This is a contribution of the Isua Multidisciplinary Research Project generously supported by the Danish Natural Science Research Council, by the Commission for Scientific Research in Greenland and by the Minerals Office of the Greenland Government (*now* Bureau of Minerals and Petroleum). Thanks are expressed to M.T. Rosing and W.S. Watt for constructive comments on a previous manuscript.

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Archaean and Palaeoproterozoic orogenic processes: Danish Lithosphere Centre studies of the Nagssugtoqidian orogen, West Greenland

Flemming Mengel, Jeroen A. M. van Gool, Eirik Krogstad and the 1997 field crew

The Danish Lithosphere Centre (DLC) was established in 1994 and one of its principal objectives in the first five-year funding cycle is the study of Precambrian orogenic processes. This work initially focused on the thermal and tectonic evolution of the Nagssugtoqidian orogen of West Greenland.

During the first two field seasons (1994 and 1995) most efforts were concentrated in the southern and central portions of the orogen. The 1997 field season was the third and final in the project in the Nagssugtoqidian orogen and emphasis was placed on the central and northern parts of the orogen in order to complete the lithostructural study of the inner Nordre Strømfjord area and to investigate the northern margin of the orogen (NNO in Fig. 1).

This report is partly a review of selected research results obtained since publication of the last Review of Greenland activities (van Gool *et al.* 1996), and also partly a summary of field activities in Greenland during the summer of 1997.

Background for project

The overall aim of DLC's Nagssugtoqidian project is to establish the large-scale geometry of the orogen, to identify the lithotectonic components and their age and to characterise the dynamic aspects of the evolution, including the structural, metamorphic and magmatic variations.

The southern boundary of the orogen (southern Nagssugtoqidian front, SNF in Fig. 1), was defined by Ramberg (1949) on the basis of progressive structural reworking of the Palaeoproterozoic Kangâmiut dyke swarm. South of the SNF, the dykes are discordant with respect to the structures in the Archaean granulite facies gneisses. North of the SNF, the dykes and their country rocks are deformed and metamorphosed together. The geometry of the SNF was first described in detail by Escher *et al.* (1970, 1975), and was viewed as a frontal thrust, across which the southern Nagssugtoqidian orogen was translated towards the southern foreland.

Figure 1 shows the main lithotectonic units of the Nagssugtoqidian orogen (from Marker *et al.* 1995; van Gool *et al.* 1996). The southern foreland consists of Archaean granulite facies tonalitic-granodioritic gneisses cut by mafic dykes of the Palaeoproterozoic Kangâmiut swarm. In the SNO (southern Nagssugtoqidian orogen) gneisses and dykes from the foreland were deformed and metamorphosed in amphibolite facies and transposed into NNW-dipping structures during SSE-directed ductile thrusting. Towards the contact between the SNO and CNO (central Nagssugtoqidian orogen), the metamorphic grade increases to granulite facies (Korstgård 1979). The SNO–CNO boundary is defined by the Ikertooq steep belt, a regionally pervasive high strain zone which also marks the northernmost occurrence of the Kangâmiut dyke swarm. The CNO is characterised by a southern part with a generally steep and penetrative ENE-trending structural grain, whereas the northern CNO comprises alternating steep and shallow-dipping structures ('steep' and 'flat' belts, respectively). Northwards, the CNO is delimited by the Nordre Strømfjord steep belt (Bak *et al.* 1975a, b; Hanmer *et al.* 1997), a regionally penetrative zone of steeply dipping gneisses, including zones of localised high strain. Palaeoproterozoic calc-alkaline intrusions occur in the north-eastern CNO (*c.* 1.92 Ga Arfersiorfik quartz diorite; Kalsbeek *et al.* 1987; Kalsbeek & Nutman 1996) and south-western CNO (*c.* 1.92 Ga Sisimiut charnockite; Kalsbeek & Nutman 1996). The northern Nagssugtoqidian orogen (NNO) is dominated by variably deformed Archaean granitic to granodioritic gneisses that include units of supracrustal sequences.

Both intra- and inter-cratonic settings have been proposed to explain the development of the Nagssugtoqidian orogen in terms of a large-scale tectonic model. Bridgwater *et al.* (1973) hinted at an inter-cratonic origin and interpreted the ductile thrusting in the south-

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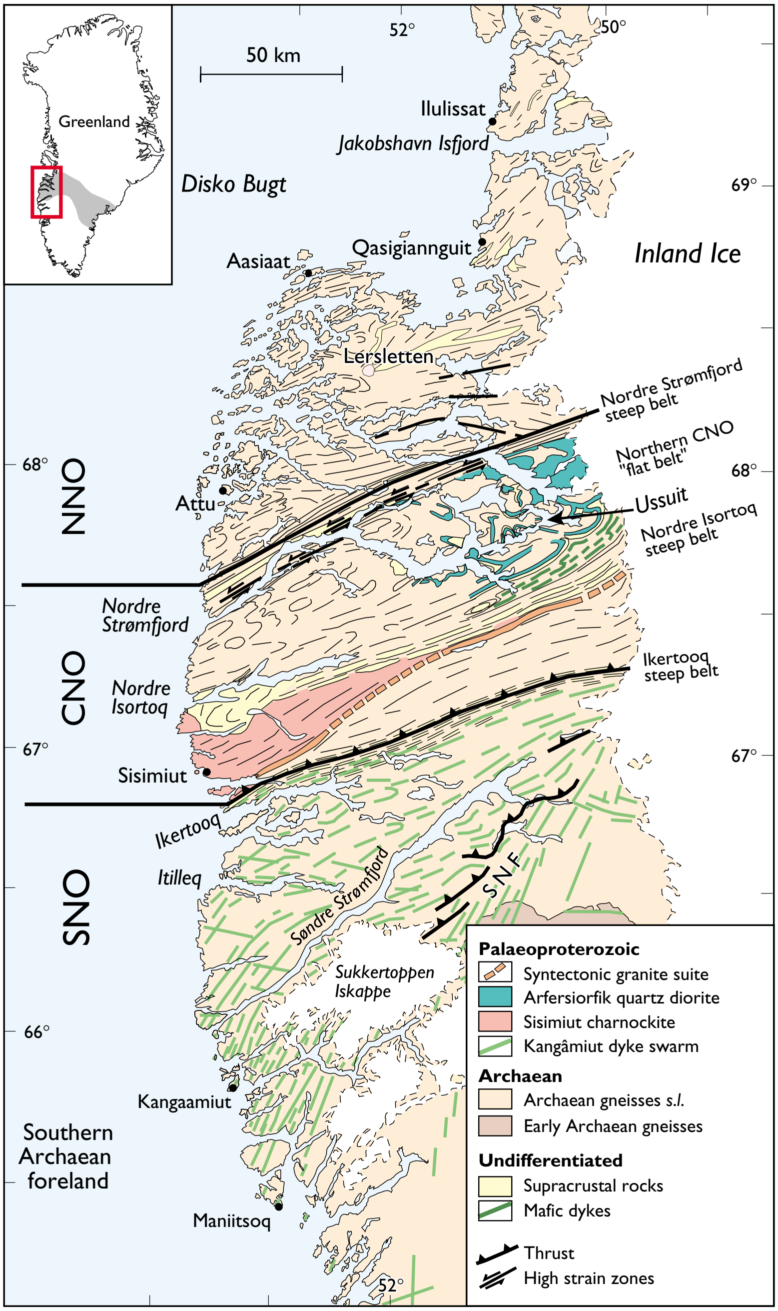
Fig. 1. Lithotectonic sketch map of the Nagssugtoqidian orogen and its southern and northern forelands. This figure includes information from Escher (1971), Allaart (1982), Marker *et al.* (1995) and van Gool *et al.* (1996). NNO, CNO and SNO are the northern, central and southern Nagssugtoqidian orogen, respectively. SNF: southern Nagssugtoqidian front. Shading on insert map shows regional extent of the Nassugtoqidian orogen across Greenland.



ern margin as indicative of a collisional origin. They had, however, insufficient data to constrain the extent of the postulated oceanic basin between the two continents. Later workers, however, focused on the large-scale transcurrent structures in the orogen, and favoured intracratonic settings to explain the geometries (e.g. Bak *et al.* 1975a, b). Geochemical and isotopic investigations of the Arfersiorfik quartz diorite (AQD) in the central part of the orogen led Kalsbeek *et al.* (1987) to revive the intercratonic model. The AQD is a calc-alkaline intrusion with geochemical and isotopic signatures similar to subduction-generated arc magmas. Based on this data, Kalsbeek *et al.* (1987) suggested that the central part of the Nagssugtoqidian orogen could contain a suture as a result of convergence, subduction and collision between two Archaean cratonic blocks.

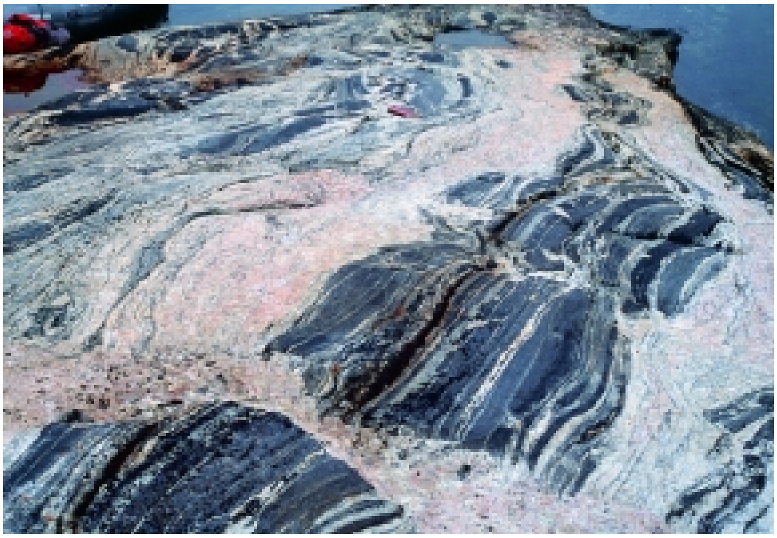


Fig. 2. Archaean basement gneisses from western Ussuit (Fig. 1). The older, mafic gneisses occur as disrupted layers in a dominantly tonalitic-granodioritic granitoid gneiss. In the foreground, a granitic pegmatite cuts both units. Notebook for scale.

Recent work by DLC in the Nagssugtoqidian orogen has partly been aimed at testing the continent–continent collision model and has been concentrated in the central and southern parts of the orogen. The work has involved an investigation of the AQD and its host-rocks in more detail, but also a characterisation of the two 'continents' in order to verify that they represent distinct blocks that were unrelated prior to collision (summarised in Marker *et al.* 1995; van Gool *et al.* 1996).

The 1997 field season focused on the central and northern parts of the Nagssugtoqidian orogen. The northern margin is poorly defined at present. There is no well-defined structural front similar to the southern margin, hence the overall geometry of the orogen is asymmetric. The northward extent of Nagssugtoqidian metamorphism is not known at present. Kalsbeek *et al.* (1987) reported undisturbed Rb-Sr and Pb-Pb isotope systems at Akulleq (25 km south-west of Aasiaat) and Aasiaat, respectively, whereas geochronological data from 15 km south-east of Aasiaat (Connelly & Mengel 1996) suggest minor thermal overprints of Palaeoproterozoic age at this latitude (Figs 1, 2).

With the above as background and framework, the main aims of the 1997 field season were:

1. To characterise the northern margin of the Nagssugtoqidian orogen and to collect data and samples necessary for outlining the northward extent of Palaeoproterozoic magmatism(?) and structural and metamorphic overprints;

2. To establish the three-dimensional geometry of structures in the inner Ussuit area (Fig. 1) in order to (1) test the thrust stack model for the interleaving of Archaean and Proterozoic gneisses (van Gool *et al.* in press); and also (2) to understand the dynamic relationships between 'steep' and 'flat' belts in the central part of the orogen;

3. To further investigate the compositional, geochronological and structural characteristics of the pre-Nagssugtoqidian basement, both internal and external to the orogen, in order to address these questions;

   a. Can a northern and southern 'continent' be identified?
   b. What are the linkages between Archaean units within the orogen and Archaean gneisses in the forelands, i.e. where is the suture?
   c. What is the control of pre-Nagssugtoqidian structures on the Nagssugtoqidian structural development?

Archaean basement rocks in the Nagssugtoqidian orogen and its forelands

Based on detailed field observations, a picture is emerging of a basement gneiss complex comprising at least three components that can be recognised throughout the orogen and within its marginal zones.

The oldest, and volumetrically least significant components are complex, polydeformed felsic to mafic

Fig. 3. Archaean basement gneisses from Kangersuneq (15 km south-east of Qasigiannguit; Fig. 1). The tonalitic-granodioritic component contains small, irregular inclusions of older, structurally more complex, mafic gneisses. Hammer for scale.

Fig. 4. Archaean basement gneisses from Orpissooq (20 km south-south-east of Qasigiannguit; Fig. 1). In this outcrop, the youngest, granitic component is dominant. The granite, locally megacrystic, contains inclusions of layered tonalitic-granodioritic gneisses (Fig. 3) and (just in front of the hammer) older mafic gneisses.

gneisses (Fig. 2). These units occur as layers, lenses or angular enclaves (centimetre- to metre-scale) included in grey tonalitic layered gneiss. Contacts are generally parallel to layering and foliation in both units, but the intrusive contacts between the older components and the younger grey gneiss are locally preserved.

This grey, tonalitic to granodioritic gneiss forms the dominant background lithology throughout the Nagssugtoqidian orogen (Fig. 3). The unit may be variably migmatitic and record several generations of migmatisation and deformation, often preserved as ghost structures in relatively homogeneous rocks.

The youngest, recognisably Archaean component of the basement gneiss complex is a granite to granodiorite which occurs as veins, sheets or larger discordant bodies (Fig. 4). The discordant boundaries are commonly transposed, but discordant relationships are locally preserved.

The zircon geochronology of the Archaean gneiss complex has been investigated both in a reconnaissance fashion (U-Pb SHRIMP: Kalsbeek & Nutman 1996) and in more detailed studies (conventional U-Pb TIMS: Connelly & Mengel 1996). The reconnaissance survey found clusters of ages around 2750–2700 Ma and 2850–2800 Ma in the dominant tonalitic-granodioritic gneisses, whereas the older components were not analysed. Similar age ranges were reported by Kalsbeek *et al.* (1987). By analysing small zircon fractions or single grains, Connelly & Mengel (1996) found that in the central and southern part of the orogen, the tonalitic-granodioritic gneisses contain igneous zircons with ages of 2870–2813 Ma and metamorphic zircons with ages between 2808 and 2750 Ma. Granitic rocks in the northern part of the orogen show intrusive ages of 2788 Ma, but apparently did not experience the post-2788 Ma deformation and metamorphism recorded elsewhere. In the southern foreland, granitic magmatism took place at *c.* 2717 Ma and at *c.* 2500 Ma (Ikertooq–Itilleq area; Connelly & Mengel 1996, unpublished data; Kalsbeek & Nutman 1996).

Albeit limited, this dataset is interpreted by Connelly & Mengel (1996, unpublished data) to show that a major intrusive event contributed new granitoid magma to the crust at 2870–2813 Ma, and that deformation and metamorphism at 2808–2750 Ma affected only the central and southern portions of the presently exposed Nagssugtoqidian orogen. Post-kinematic granite emplacement was widespread and affected an area larger than that experiencing deformation and metamorphism.

The oldest ages obtained from the Nagssugtoqidian orogen and its forelands are from immediately south of Søndre Strømfjord (Fig. 1), where zircons from gneisses in what is now defined as the Aasivik terrane have yielded U-Pb SHRIMP ages of 3784–3550 Ma (Rosing *et al.* 1997, in press). The oldest age from within the Nagssugtoqidian orogen is *c.* 3.1 Ga (F. Kalsbeek & A.P. Nutman, personal communication 1995; Nutman 1997) and was obtained from a unit of leucocratic granodioritic to granitic gneisses immediately south of inner Ussuit (Fig. 1). Sr-Nd data from a regional radiogenic isotope study (Whitehouse *et al.* 1998) also show the presence of crustal components with ages slightly in excess of 3.1 Ga.

The present geochronology dataset is incomplete, but it clearly shows that regional differences with respect to geochronologial, structural and metamorphic histories exist. The data furthermore suggest that the CNO–SNO boundary may represent a fundamental boundary, possibly separating the ‘continents’ which collided to form the Nagssugtoqidian orogen. During the 1997 field season, data and samples were collected with these issues in mind.

The stream-sediment data presented by Steenfelt (1994) also suggest overall geochemical differences between the crustal blocks north and south of Nordre Strømfjord. These differences largely coincide with the distribution of amphibolite and granulite facies, but may also reflect more fundamental differences, such as those indicated above.

Palaeoproterozoic lithologies and structural and metamorphic signatures

Southern Nagssugtoqidian front

Based on the rotation of structures in the southern Nagssugtoqidian front zone (SNF in Fig. 1) Bridgwater *et al.* (1973) and Escher *et al.* (1975, 1976) suggested that shortening in excess of 100 km was accommodated across the southern Nagssugtoqidian front (SNF). As a result of recent detailed work along the length of the exposed part of the front, Hageskov (1995) has shown the SNF to consist of segments of non-linked high-strain zones, thus suggesting that the total shortening across the front may be moderate. Two M.Sc. theses projects are at present being carried out on the structural and metamorphic contrasts across the SNF (H.E. Olsen, Geological Institute, Copenhagen University and P.S. Jensen, Geological Institute, Aarhus University) in order to constrain its development.

Structural styles in the central Nagssugtoqidian orogen

In the eastern part of CNO (Ussuit in Fig. 1), a complex thrust system separates the underlying Archaean basement gneisses from the overlying supracrustal rocks which are intruded by the the Arfersiorfik quartz diorite (Fig. 5). Due to the potential importance of this zone as representing the tectonic contact (i.e. suture) between the continent and a colliding arc, the tectonic development and structural style in the Ussuit area have received considerable attention (e.g. Passchier *et al.* 1997; Manatschal *et al.* in press; van Gool *et al.* in press).

In the Ussuit area, it can be shown that an early phase of W–NW vergent thrusting brought a lithotectonic unit consisting of supracrustal rocks intruded by the Arfersiorfik quartz diorite into tectonic contact with the underlying Archaean gneissic basement, and that this contact was repeated by subsequent thrust imbrication (van Gool *et al.* in press). These thrusts were then folded into kilometre-scale upright folds with overall ENE-trending axial planes. Based on observations in the eastern Ussuit area, Manatschal *et al.* (in press) suggest that this phase of folding was accompanied by extension along E- to ENE-dipping shear zones.

The early contractional thrust structures, which provide crucial information about the geometry and dynamics of early phases of the collisional event, are only rarely preserved; generally the thrusts are overprinted and obliterated by later open to tight upright folds, which dominate the present day structural grain.

Fig. 5. Tectonic contact between Archaean basement gneisses and a Palaeoproterozoic package consisting of supracrustal rocks intruded by the Arfersiorfik quartz diorite (see text for discussion). Bow of *Kissavik* indicates the south-dipping contact between Archaean gneisses (lower left) and Palaeoproterozoic rocks (upper right). Cape behind *Kissavik* is 380 m high. Locality: western Ussuit (Fig. 1).

Structures and lithologies in the northern Nagssugtoqidian orogen and foreland – linkage with the Rinkian?

The reconnaissance carried out in the Disko Bugt area (between 68°30′ and 69°30′N; Fig. 1) was aimed at characterising the poorly known northern margin of the Nagssugtoqidian orogen and at studying the relationships between the NNO and the better understood Rinkian belt farther north (e.g. Henderson & Pulvertaft 1987; Grocott & Pulvertaft 1990).

The basement in the Disko Bugt area south of Jakobshavn Isfjord is composed of layered amphibolite facies gneisses, comprising the three main components also described from elsewhere in the Nagssugtoqidian orogen. The oldest, mafic component is represented by layers, as well as blocks and fragments occurring in agmatitic zones, enclosed within the dominant grey, tonalitic to granodioritic layered gneiss (Fig. 3). The youngest granitic component is locally dominant, and occurs as sheets and dykes or as large, megacrystic bodies (Fig. 4). The larger bodies contain inclusions of both the mafic and tonalitic components, both showing a complex pre-granite structural history (Fig. 4). Discordant relationships between the granite and its host rocks are generally preserved, but the granitic layers and bodies are always folded along with its host rocks and have a variably developed foliation. The 'younger granitic' component described above, is presumably temporally and compositionally similar to the Rodebay granodiorite (Garde 1994), which occurs mainly north of Jakobshavn Isfjord and which is characterised by a single, simple fabric.

Two groups of supracrustal rocks occur as units interleaved with the Archaean gneiss complex. The first group is abundant near Jakobshavn Isfjord (Fig. 1) and is dominated by layered amphibolites (see also Henderson 1969; Escher 1971; Garde 1994). These rocks are intruded by grey tonalitic sheets assumed to belong to the Archaean complex.

The other group of supracrustal rocks occurs south of Jakobshavn Isfjord and is apparently similar to the supracrustal rocks from Lersletten (Fig. 1) farther south (e.g. Henderson 1969; Marker *et al.* 1995). This package is dominated by psammitic to pelitic lithologies and amphibolites with minor marbles, calc-silicate rocks and quartzites. Locally, these rocks are cut by two-mica granite sheets. Preliminary petrographic and thermobarometric studies (F. Mengel & M. Marker, unpublished data) on samples from Lersletten show staurolite-garnet-sillimanite-biotite-muscovite assemblages (kyanite found near Qasigiannguit, Fig. 1), with clear evidence of advanced replacement of staurolite in some lithologies. The stable parageneses suggest metamorphic peaks at lower to middle amphibolite facies conditions. The age of sources, deposition and metamorphism(s) of the supracrustal rocks is at present not known. The supracrustal rocks and the basement gneisses are cut by mafic dykes, which appear similar to the Kangâmiut dykes much farther south. This correlation is tentative, and awaits geochronological and geochemical confirmation.

The contact between Archaean gneisses and felsic supracrustal rocks is commonly mylonitised with subhorizontal, ENE-trending stretching lineations. Although a consistent sense of motion has not been determined so far, a top-to-east movement sense seems predominant. The earliest folds recognised in the area south of Ilulissat are mesoscopic, tight to isoclinal folds, generally recumbent. These are overprinted by large-scale, open, upright, shallowly ENE-plunging folds.

Although based only on a short visit (about one week) it appears that both the style and sequence of structural events in the northern NNO up to Ilulissat are comparable to that described for CNO (see above), namely involving (1) early shearing and thrusting along contacts between basement gneisses and supracrustal rocks, and (2) recumbent folding followed by (3) large scale upright folding with ENE-trending axial planes. If this correlation is correct, it follows that many of the observed structures in the NNO are of Nagssugtoqidian age, however, geochronological confirmation is clearly needed.

North of the Nagssugtoqidian orogen, the Rinkian belt is characterised by large-scale, west vergent recumbent folds (fold nappes) and dome structures which are considered to be Proterozoic (e.g. Grocott *et al.* 1987; Henderson & Pulvertaft 1987; Garde & Steenfelt, in press). The structural characteristics of the NNO are transitional between those in the CNO and the Rinkian. The NNO does not, however, contain structural evidence for the presence of gneiss domes.

It is worth re-emphasising that while the southern margin of the Nagssugtoqidian orogen is structurally well-defined (see above), the northern limit of clearly Nagssugtoqidian structural and metamorphic signatures cannot be precisely delineated and appears to grade, via a transitional zone, into the southern part of the Rinkian belt. The Nagssugtoqidian orogen and Rinkian belt may thus represent different responses to the same tectonic forces, and should not be viewed as unrelated orogens, but rather as different expressions of the same orogenic event.

Proterozoic mafic dykes – age data for the Kangâmiut dyke swarm

The Kangâmiut dyke 'swarm', which played a key role in the identification and definition of the Nagssugtoqidian orogen (Ramberg 1949), has long been known to include several generations of dykes (e.g. Windley 1970; Escher *et al.* 1975; Jack 1978; Nash 1979a, b; Mengel *et al.* 1997 and many others). The earliest generation is E–W trending, and normally orthopyroxene- or olivine-bearing and is cut by the NNE- to NE-trending main suite. Locally, there is evidence of an intervening suite with broadly the same composition and trend as the main swarm.

Kalsbeek *et al.* (1978) presented Rb-Sr data showing a 1950 ± 60 Ma intrusive age for the main swarm, and later U-Pb zircon (SHRIMP) analyses on the same and similar samples broadly confirmed this age (*c.* 2.04 Ga; Kalsbeek & Nutman 1996; Nutman *et al.* in press).

Recently, Williger*s et al.* (1998) presented ^{40}Ar-^{39}Ar hornblende cooling age data from Kangâmiut dykes in the southern foreland. The data fall in two groups clustering around *c.* 2.02 Ga (Kangaamiut–Itilleq area; Fig. 1) and *c.* 2.4 Ga (near Maniitsoq; Fig. 1). These ages are interpreted by Willigers *et al.* (1998) to show (1) the presence of > 2.4 Ga mafic dykes in the Kangâmiut dyke 'swarm' in the Maniitsoq area, (2) that the dykes in the southern foreland were affected by a phase of metamorphism pre-dating (and unrelated to) Nagssugtoqidian magmatism and metamorphism (*c.* 1.92–1.80 Ga), (3) that the area around Maniitsoq was not heated above *c.* 530°C (closure temperature for the diffusion of Ar in hornblende; Harrison 1981) after 2.4 Ga, and (4) that hornblendes from the area between Kangaamiut and Itilleq were not reset after 2.02 Ga, from which it follows that the Nagssugtoqidian metamorphic temperatures in this region never exceeded *c.* 530°C. It is notable, that the *c.* 2.02 Ga Ar-Ar cooling ages overlap within error with the *c.* 2.04 Ga U-Pb zircon ages referred to above.

The thermobarometric data presented by Mengel *et al.* (1997) showed that metamorphic garnet-bearing assemblages in dykes in the foreland between Maniitsoq and Itilleq (Fig. 1; including many of those studied by Willigers *et al.* 1998) equilibrated at pressures up to 10 kbar. Mengel *et al.* (1997) assumed that these overprints were of Nagssugtoqidian age. However the new ^{40}Ar-^{39}Ar data suggest that pre-Nagssugtoqidian thermal events are involved.

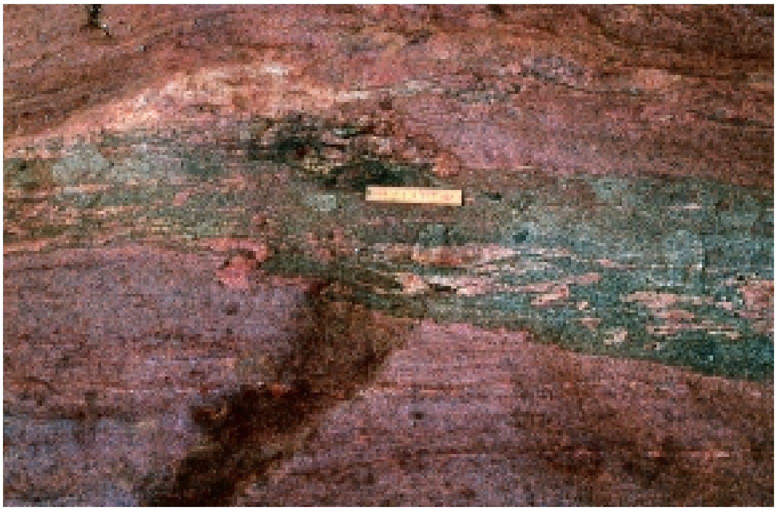
Work in progress is aimed at confirming these crucial new data and at evaluating the consequences for previous models for the pre-Nagssugtoqidian evolution of this area.

Proterozoic mafic dykes – relation to supracrustal rocks

Prior to the 1997 field season, Kangâmiut dykes had only been observed cutting supracrustal rocks in a few places (e.g. at the mouth of Itilleq: Jack 1978), and consequently this had been interpreted to indicate that deposition of some of the supracrustal packages, e.g. in the Ikertooq area, post-dated emplacement of the Kangâmiut dykes at *c.* 2.04 Ga, which is consistent with results from provenance studies (Nutman *et al.* in press).

Fig. 6. Two sets of mafic dykes from Tasersuaq (*c.* 20 km east-north-east of inner Ikertooq; Fig. 1). The earlier dykes and the layered host gneiss are folded in an overturned antiform which is cross-cut by a shallow-dipping dyke. Note slight off-set along younger dyke (e.g. just left of the centre of the photograph). Wall is *c.* 200 m high.

Fig. 7. Discordant mafic dyke in inner Ikertooq (Fig. 1). Detail of migmatised mafic dyke (grey) cutting pelitic supracrustal rocks (brown). The contact and the migmatitic veins are intensely folded. The foliation in the dyke is parallel to foliation and layering in the supracrustal gneiss. Scale bar is 10 cm.



Mafic dykes, tentatively correlated with the Kangâmiut dyke swarm, are found throughout Ikertooq. In the Avalleq and Akulleq areas (southern and central arms of inner Ikertooq; Fig. 1) most dykes are clearly discordant, while the majority of the dykes in Maligiaq (northern arm of inner Ikertooq; Fig. 1) appear to have been transposed into parallelism with the strong E–W structural grain characterising the SNO-CNO boundary zone.

Clearly discordant dykes of mafic composition were found cutting concordant mafic layers and dykes in penetratively foliated gneisses in 1995 (Fig. 6; van Gool *et al.* 1996), and during the 1997 field season discordant dykes were observed in the supracrustal rocks in Maligiaq (inner Ikertooq). The dykes cutting metapelitic supracrustal rocks are up to 0.5 m wide, highly irregular and strongly deformed, with a foliation that is parallel to that in the supracrustal rocks (Fig. 7). As a result of interaction between the hot dyke-magma and the hydrous pelite, the contact zone is strongly migmatised, and locally the dykes occur as irregular fragments, lenses or layers in delicately folded melt-rich migmatites, thus rendering identification difficult. Disrupted mafic to intermediate lenses occurring in migmatitic supracrustal rocks in Maligiaq are comparable in all aspects to the clearly discordant dykes, and may well represent dyke fragments. Preliminary geochemical analysis of one such dyke shows a composition different from average Kangâmiut dykes, and even disregarding the strong contamination from the supracrustal host-rock (enrichment in e.g. Na, K, Ba) this dyke is unlikely to belong to the main Kangâmiut swarm.

The observations show that not all mafic dykes in the Ikertooq area are the same age. It is, however, not clear whether the discordant dykes post-date the development of Nagssugtoqidian fabrics, or whether they are Kangâmiut dykes cutting Archaean penetrative fabrics in areas with older dykes (Archaean?) that escaped thorough Nagssugtoqidian deformation. Answers to these questions are presently being pursued by a combination of geochemical and geochronological methods.

Age of supracrustal rocks in the Nagssugtoqidian orogen

Supracrustal rocks occur in several distinct settings within the Nagssugtoqidian orogen (see also Fig. 1) and correct interpretations of their sources and ages are important for understanding the dynamic evolution of the orogen. Recently, an analytical programme was initiated in order to study the sources and ages of deposition of the various supracrustal suites in the SNO and CNO (Marker *et al.* 1997). The analytical methods employed include U-Pb analysis of zircons by NORDSIM ionprobe (M. Whitehouse) and by ICP-MS laser ablation (D. Scott), and Sm-Nd and Rb-Sr whole-rock isotope analysis (O. Stecher). The preliminary results of this study are summarised below (mainly from Marker *et al.* 1997).

The metasediments occurring along the SNO–CNO boundary (along Ikertooq; Fig. 1) have Sm-Nd model ages (T_{DM}, DePaolo 1981) of *c.* 2.8 Ga which indicate that their likely provenance are the surrounding *c.* 2.8 Ga Archaean gneisses. Zircons, on the other hand, have a range of $^{207}Pb^*/^{206}Pb^*$ ages, including an important component, probably metamorphic in origin, at 1.84 Ga. In a SHRIMP U-Pb zircon study of a metasediment from the same area, Nutman *et al.* (in press) also found ages around 2.8–2.7 Ga and 1.85 Ga, but in addition they obtained a cluster of $^{207}Pb^*/^{206}Pb^*$ ages at *c.* 2.4 Ga, which they interpreted to represent a Palaeoproterozoic component. Sediments immediately south of the SNO–CNO boundary show slightly younger T_{DM} ages (*c.* 2.4 Ga), also suggesting substantial contributions from Palaeoproterozoic sources (Marker *et al.* 1997).

The supracrustal package occurring along Nordre Isortoq (Fig. 1) was known from earlier work to be cut by *c.* 2.8 Ga orthopyroxene-bearing granitoid rocks (J. Connelly, unpublished data). T_{DM} ages are in agreement with an Archaean source for the Nordre Isortoq supracrustal rocks. In contrast, T_{DM} ages from supracrustal rocks in the eastern extension of the belt suggest a substantial Palaeoproterozoic component. It should be noted that the supracrustal units in the belt are not continuous (as also indicated schematically in Fig. 1), however, the lateral change in source-ages indicates either that two different supracrustal packages were tectonically juxtaposed, or reflects significant along-strike variations in the source rocks at the time of deposition.

Detrital zircon studies of allochthonous supracrustal units in inner Nordre Strømfjord have yielded mainly Palaeoproterozoic ages around 2100–2000 Ma (Nutman *et al.* in press). T_{DM} ages (*c.* 2.3 Ga) also suggest the presence of a significant Palaeoproterozoic component in the source. However, rocks of these ages are not known from the central part of the orogen, so the Palaeoproterozoic component must be distally derived. Sediments in the western and central part of the Nordre Strømfjord steep belt (Fig. 1) show similar detrital zircon age spectra and T_{DM} ages as the sediments farther east.

The first-order pattern emerging above is that supracrustal rocks in the SNO–CNO boundary region are largely derived from Archaean precursors, whereas those in the northern CNO are dominated by distally derived Palaeoproterozoic material.

Concluding remarks

This report presents the current status of work on the Nagssugtoqidian orogen being carried out by a large group of researchers (including participants of 1994 and 1995 field work; see Marker *et al.* 1995; van Gool *et al.* 1996).

Data at present available are in accord with the model describing the development of the Nagssugtoqidian orogen in terms of an early phase of closure of an ocean basin through subduction, and a second phase of collision, crustal thickening and later exhumation. It has also become clear that the Archaean basement experienced an orogenic cycle, including magmatism, deformation and metamorphism, prior to Nagssugtoqidian orogeny.

Ongoing efforts will focus on some of the geochronological, structural and metamorphic problems outlined above, and will allow us to address some of the following important topics:

1. Characterisation of the Archaean basement, including the geometry and dynamics of crustal blocks prior to Nagssugtoqidian orogeny;

2. Emplacement ages and exhumation history of mafic dyke swarm(s) in the southern foreland;
3. Sources and timing of deposition of supracrustal rocks: geodynamic significance;
4. Establishment of a detailed structural chronology for the multiply thrust-imbricated and folded tectonic contact between Archaean and Palaeoproterozoic units in the CNO;
5. Linkages with the Rinkian belt to the north;
6. Westward correlations with the Torngat–Baffin orogens in north-eastern Canada;
7. *T-t* evolution of the Nagssugtoqidian orogen subsequent to peak metamorphism.

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Reassessment of the north-western border zone of the Palaeoproterozoic Ketilidian orogen, South Greenland

Adam A. Garde, Brian Chadwick, Ken McCaffrey and Mike Curtis

As part of ongoing research into the plate tectonic setting of the Palaeoproterozoic Ketilidian orogen led by the Geological Survey of Greenland and Denmark, four geologists from Denmark and the U.K. re-examined parts of the north-western border zone in July–August 1997. The field work was generously supported by the Danish Natural Science Research Council and the Carlsberg Foundation. One team studied the Proterozoic (Ketilidian) sedimentary and volcanic rocks and the regional structure, working from six inland camps along the variably deformed Archaean–Proterozoic unconformity between Midternæs and Qoornoq and on Arsuk Ø (Fig. 1). A second team investigated the plutonic and kinematic evolution of the Kobberminebugt area at the north-western margin of the Julianehåb batholith (Fig. 1); the latter forms the central part of the Ketilidian orogen (Chadwick & Garde 1996). In addition, samples of volcanic and granitic rocks were collected for geochemical studies and dating of depositional and tectonic events.

The first systematic study of the Ketilidian orogen took place in the 1960s and was largely concentrated in its western and southern parts (Allaart 1976). Essential new data from the central and eastern parts of the orogen were acquired during the Survey's SUPRASYD project (1992–1996; e.g. Garde & Schønwandt 1994, 1995; Garde *et al.* 1997; Stendal *et al.* 1997), which was initiated with the aim of assessing the potential for mineral resources in supracrustal sequences (Nielsen *et al.* 1993). In the course of the SUPRASYD project a new plate-tectonic model for the entire orogen was also published (Chadwick & Garde 1996), in which the orogen is viewed as the result of oblique convergence

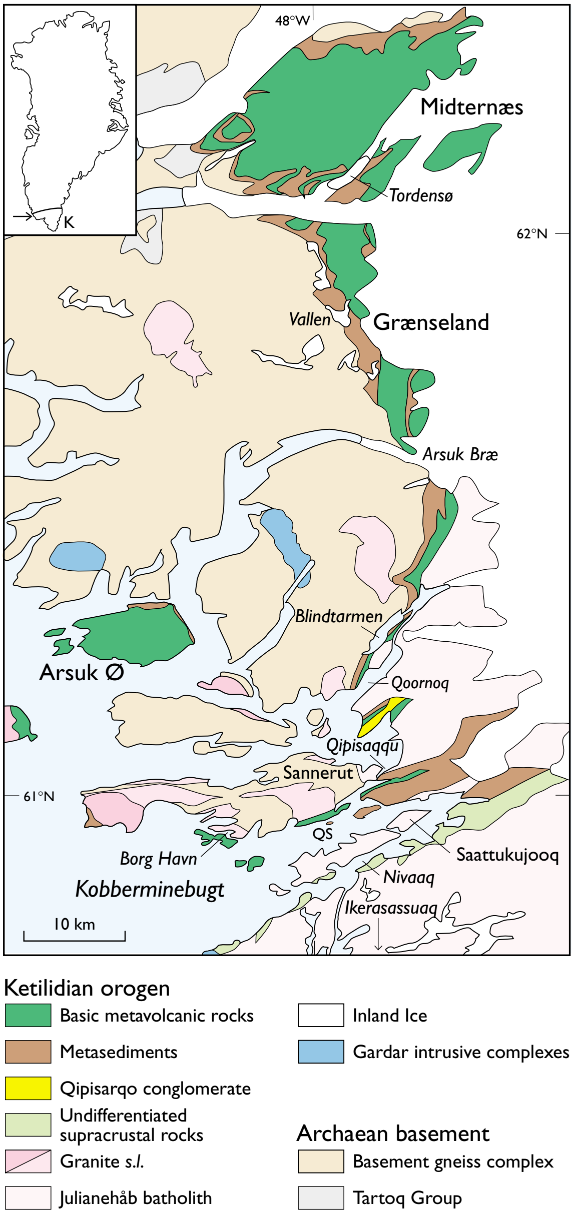


Fig. 1. Simplified geological sketch map of the north-western border zone of the Ketilidian orogen, with place names mentioned in the text. QS: Qaqortup Sallersua. K (index map): Ketilidian orogen. Map based on Geological map of Greenland, 1:500 000, Sydgrønland, sheet 1 (Allaart 1975).

Geology of Greenland Survey Bulletin 180, 111–118 (1998)

Table 1. Lithostratigraphy of Ketilidian supracrustal rocks in the Grænseland area

- Sortis Group
- Vallen Group
  - Grænsesø Formation
  - Blåis Formation
  - Zigzagland Formation
    - Upper Zigzagland Formation
      - Dolomite Shale Member
      - Banded Quartzite Member
      - Ore-Conglomerate Member
    - Lower Zigzagland Formation
      - Rusty Dolomite Member
      - Varved Shale Member
      - Lower Dolomite Member
      - Residual deposits on the sub-Ketilidian surface

Simplified after Bondesen (1970)

between the Archaean craton of southern Greenland and a supposed oceanic plate located south of the present orogen, which was subducted towards the north. Chadwick & Garde (1996) also suggested a new division of the Ketilidian orogen into a 'Border Zone' adjacent to the Archaean craton, the 'Julianehåb batholith' (formerly the Julianehåb granite) in the central part of the orogen, and the 'Psammite Zone' and 'Pelite Zone' to the south-east, which largely consist of deformed and metamorphosed erosion products derived from the evolving batholith.

The north-western border zone and the Ketilidian supracrustal sequences were mapped in the 1960s by Harry & Oen Ing Soen (1964), Watterson (1965), Bondesen (1970), Higgins (1970), Muller (1974), Berthelsen & Henriksen (1975) and Pulvertaft (1977). It was shown that an Archaean gneiss complex (part of the Archaean craton of southern West Greenland) and Palaeoproterozoic basic igneous rocks (the so-called 'MD' (metadolerite) dyke swarms and related intrusions), and the unconformably overlying Ketilidian supracrustal rocks are progressively affected by Ketilidian deformation and metamorphism towards the Julianehåb batholith in the south and south-east. Boundary relationships were reviewed by Henriksen (1969). Where the Ketilidian supracrustal rocks are best preserved at Midternæs and Grænseland, Bondesen (1970) and Higgins (1970) divided them into the Vallen Group, which largely consists of sedimentary rocks (Table 1), and the overlying Sortis Group, in which basic pillow lavas and related doleritic to gabbroic sills predominate. Supracrustal rocks of presumed Palaeoproterozoic age further south have previously been referred to as the Qipisarqo and Ilordleq Groups (Berthelsen & Noe-Nygaard 1965; Allaart *et al.* 1969).

Based on data collected in the 1960s, the earliest plate-tectonic interpretation of the Ketilidian orogen included a prominent suture in Kobberminebugt (Windley 1991). However, other critical aspects of Windley's model were not substantiated during the Survey's studies in 1992–1996 (Chadwick *et al.* 1994; Chadwick & Garde 1996), and a re-evaluation of the north-west border zone was therefore a natural focus of subsequent investigations.

Banded iron formation in central Grænseland and related rocks on Arsuk Ø

We have little to add to the original lithological descriptions of most sedimentary and metavolcanic-metagabbroic rock units by previous workers. However, based on observations in the lowermost part of the Vallen Group in central Grænseland 3 km south of lake Vallen (Fig. 2), we propose a reinterpretation of the Ore-Conglomerate Member of the Upper Zigzagland Formation (Table 1; Bondesen 1970) as an iron formation.

A few metres of the Archaean orthogneisses immediately below the Ketilidian supracrustal sequence were leached and carbonate-enriched by percolating groundwater in Ketilidian time (Bondesen 1970). A basal conglomerate with unsorted clasts of orthogneiss, pegmatite, vein quartz, dolomite and green mica schist, up to *c.* 20 cm in size, rests unconformably on the altered basement and is overlain by the Lower Dolomite and Varved Shale Members, each *c.* 15 m thick: the latter member comprises dark laminated slates with grading and fine-scale cross-bedding. The Rusty Dolomite Member is 0.5 to 1 m thick. The overlying unit (Table 1) was named the Ore-Conglomerate Member by Bondesen (1970), who described it as an oligomict conglomerate consisting of boulders of grey to white cherty quartzite set in a matrix of magnetite or locally pyrite. Chert-podded banded iron formations in the Archaean Hamersley Group, Australia (Trendall & Blockley 1970; Trendall 1983), are very similar in appearance to the Ore-Conglomerate Member seen by us in Grænseland. Consequently, we interpret this Member as a chert-podded banded iron formation, in which some chert pods superficially resemble rounded clasts of chert. About 3 km south of Vallen it has a total thickness of 16 m and is largely composed of variably podded chert layers 8–10 cm thick which alternate with 2–3 cm thick

Fig. 2. The basal part of the Ketilidian succession at Vallen in central Grænseland with the Archaean basement in the left background, viewed towards west-north-west. Relief is about 500 m with tents in right foreground.

layers of recrystallised, fine-grained magnetite (Fig. 3). Planar millimetre-scale chert-magnetite layering occurs in a *c.* 10 cm thick zone near the base of the member. In a *c.* 1 m thick zone in the middle of the member the podded chert layers are only 2–3 cm thick and alternate with few millimetre-scale magnetite seams. Near the top of the member the chert layers increase in thickness and the magnetite content decreases. The lowermost 10 m of the overlying unit, the Banded Quartzite Member of Bondesen (1970), comprises calcareous and quartzitic chert-pebble conglomerates and impure bedded quartzites and siltstones.

A second possible category of iron formation was found in shoreline outcrops of the Isua Formation of Muller (1974) on the headland in the extreme north-west of Arsuk Ø. Intensely deformed greywackes with local graded bedding pass westwards into pyritic black phyllites and cherts which are followed on the headland itself by bedded and podded cherts with intervening amphibole garbenschiefer with disseminated pyrite and pyrrhotite; veins of carbonate are common. We suggest that the coarsely bedded chert-amphibole-sulphide-carbonate association on Arsuk Ø is an iron formation of mixed silicate-sulphide-carbonate facies.

Structure and kinematics of the border zone between Midternæs and Arsuk Ø

Strongly aided by the meticulous investigations of previous workers (Bondesen 1970; Higgins 1970; Muller 1974; Berthelsen & Henriksen 1975; S.B. Jensen, unpublished Survey documents) we were able to establish the deformation chronology and kinematics in each of the areas examined along the Archaean-Proterozoic boundary (Fig. 1). However, it proved difficult to integrate these observations into a coherent structural and kinematic model for the entire region. Furthermore, it was difficult to distinguish between Archaean and Proterozoic deformation structures in the basement terrain.

In the Ketilidian supracrustal rocks between Midternæs and Qoornoq we recognised two principal Ketilidian phases of deformation, here designated D1 and D2. Deformation is generally much more pronounced in the sedimentary rocks than in the basic igneous lithologies. A third phase, D3, was observed locally but does not appear to have regional significance. An interpretative sketch of the Ketilidian structure in the area between Midternæs and Qoornoq is shown in Figure 4.

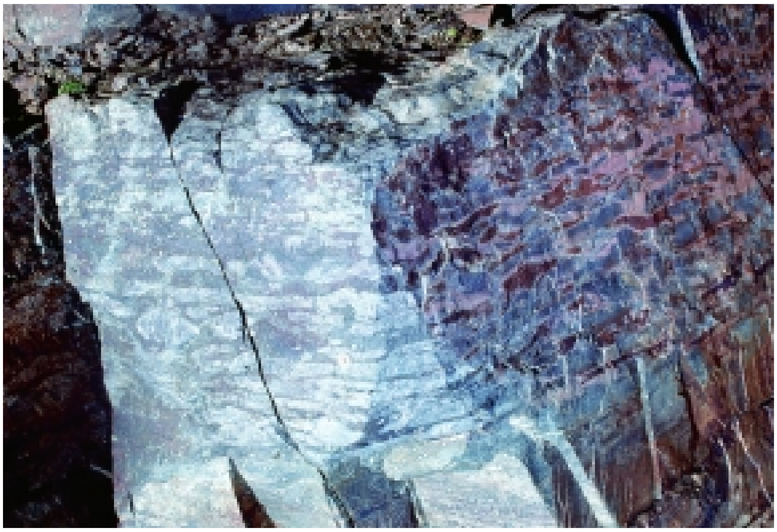


Fig. 3. Podded banded iron formation in the Lower Zigzagland Formation, central Grænseland *c.* 3 km south of Vallen. Height of photograph *c.* 80 cm.

In the south-western part of Midternæs, west of Tordensø, NNE-trending upright folds with subhorizontal plunges and coaxial stretching lineations indicate NNW–SSE shortening. Similar structures in sedimentary rocks of the Sortis Group in the extreme north-east part of Grænseland suggest a structural link with Midternæs.

In other parts of northern and central Grænseland there is repeated evidence of thrust movements with hanging wall transport towards the west-south-west and south-west. The principal detachments appear to be within the Dolomite Shale Member of the Upper Zigzagland Formation and in the Grænsesø Formation just below the massive igneous rocks of the Sortis Group (Table 1; see Bondesen 1970 for details of the stratigraphy). There are few signs of Proterozoic deformation in the Archaean orthogneisses immediately below the Ketilidian sediments in central Grænseland; no observations were made within the basement terrain further west.

In the area south of Arsuk Bræ, both the supracrustal rocks and the underlying crystalline basement were affected by Ketilidian deformation (Henriksen 1969; Berthelsen & Henriksen 1975). Within the basement we observed several moderately steep, E- to ESE-dipping mylonite zones with sinistral displacements affecting Palaeoproterozoic 'MD' dykes and hence presumably of Ketilidian age; the mylonites are correlated with penetrative D1 deformation in the adjacent cover rocks.

At Blindtarmen the Ketilidian supracrustal rocks west of the Qôrnoq augen granite (Berthelsen & Henriksen 1975) form a steep NNE-trending belt of intensely deformed schists and amphibolites bounded by Archaean orthogneiss to the west. In the east, sheets of Qôrnoq augen granite were intruded into the supracrustal rocks prior to or during D1, and there is clear evidence of non-coaxial D1 deformation with subhorizontal sinistral displacement both in the supracrustal rocks and within the granite; correlation with D1 sinistral displacement south of Arsuk Bræ seems straightforward. A large asymmetric fold of D2 age in the south-east of the area may likewise be linked with sinistral non-coaxial deformation. In the intensely deformed basement gneisses immediately west of the supracrustal belt the predominant sense of movement appears to be dextral, but it is uncertain if these structures are Proterozoic, and correlation with kinematics in the adjacent supracrustal rocks is unclear.

In the western and north-western parts of Arsuk Ø we confirmed previous recognition of an early phase of deformation by Muller (1974). His D1 upright, N–S trending folds in the sedimentary rocks indicate E–W compression. The F1 folds were folded by a large upright F2 syncline plunging west-south-west, with its axial trace through the south-eastern part of the island. Both sets of structures seem unrelated to the structures between Midternæs and Qoornoq, although the F2 syncline on Arsuk Ø may correlate with the D1 curvature and steepening of the Ketilidian cover rocks between Arsuk Bræ and Qoornoq (Fig. 4). Furthermore, it is uncertain to what extent the Archaean basement participated in the Ketilidian deformation events on Arsuk Ø, and whether a major unexposed detachment zone exists near the base of the supracrustal sequence.

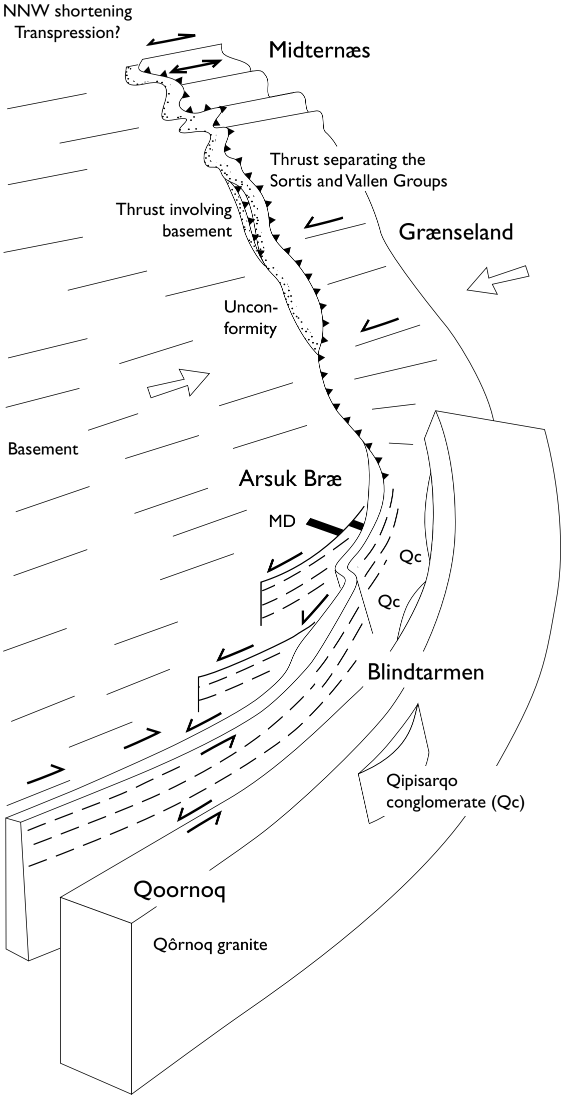


Fig. 4. Interpretative sketch of the Ketilidian structure in the area between Midternæs and Qoornoq.

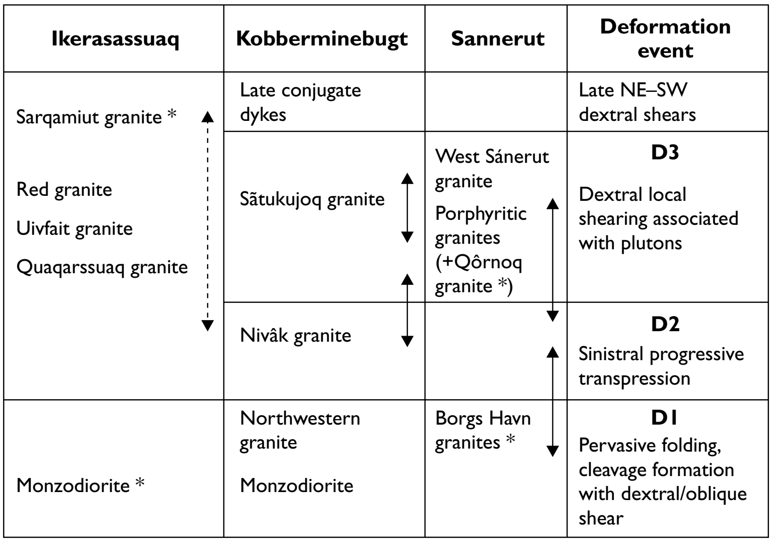
Intrusive and kinematic events in the Kobberminebugt area

Field work in 1997 in the Kobberminebugt area had two objectives: first, an assessment of the deformation history in the supracrustal rock units which are tentatively correlated with the Ketilidian rocks of the Vallen and Sortis Groups to the north-east and which occur as screens between intrusive members of the Julianehåb batholith; second, establishment of the emplacement histories, relative ages and deformation of several granitic intrusions mapped previously (see Berthelsen & Henriksen 1975; Pulvertaft 1977). A U-Pb zircon dating programme on samples from some of these intrusions and a granite clast from the Qipisarqo conglomerate south-east of Qoornoq (Berthelsen & Henriksen 1975) has been initiated in order to establish the timing of the main intrusive and tectonic events in the border zone and correlate their development with other parts of the orogen.

Rocks and structures in three subareas were investigated: (1) Ikerasassuaq south of Kobberminebugt; (2) central Kobberminebugt; and (3) the island of Sannerut. A tentative correlation between established deformation events D1–D3 in the Kobberminebugt area and the emplacement of granitic plutons is shown in Fig. 5. The deformation events designated D1–D3 in the Kobberminebugt area may not be directly correlatable with D1–D3 between Midternæs and Qoornoq (see also conclusions below).

Screens of supracrustal rocks in shoreline outcrops in central Kobberminebugt are largely mica schists and amphibolites with subordinate conglomerates, quartzites, semipelites and volcaniclastic rocks. A steep, intensely developed cleavage with a subhorizontal mineral stretching lineation suggests a high degree of flattening. Graded bedding younging south-west and a first (S1) cleavage are well preserved in semipelites on a small island in central Kobberminebugt called Qaqortup Sallersua. Prefolding pegmatite veins in the semipelites display dextral asymmetric boudinage, and a relatively consistent ‘Z’ geometry of upright, SSW-plunging F1 minor folds likewise suggests D1 dextral shear parallel to the trend of Kobberminebugt. Three sheet-like bodies of the Borgs Havn granite on Sannerut were emplaced parallel to bedding and S1 cleavage and deformed by D2 structures.

The second phase of deformation (D2) is confined to localised zones parallel to the general ENE–WSW trend of the orogen. Refolding of isoclinal F1 folds by tight, upright F2 folds with moderate to steep, west plunging, curvilinear fold axes gave rise to Type 1, 2 and 3 interference patterns of Ramsay (1967). The S2 cleavage commonly displays a low-angle clockwise fold transection and sinistral extensional shears, with local evidence for a progressive, sinistral, non-coaxial component to the deformation locally preserved. Early fabrics in the Nivâk granite on the south coast of Kobberminebugt indicate that it was emplaced in a sinistral shear regime of presumed D2 age.



Ikerasassuaq	Kobberminebugt	Sannerut	Deformation event
Sarqamiut granite * Red granite Uivfait granite Quaqarssuaq granite	Late conjugate dykes		Late NE–SW dextral shears
	Sâtukujoq granite	West Sánerut granite Porphyritic granites (+Qôrnoq granite *)	**D3** Dextral local shearing associated with plutons
	Nivâk granite		**D2** Sinistral progressive transpression
Monzodiorite *	Northwestern granite Monzodiorite	Borgs Havn granites *	**D1** Pervasive folding, cleavage formation with dextral/oblique shear

Fig. 5. Correlation of deformation events D1–D3 in the Kobberminebugt area with emplacement of granitic intrusions. Only the relative ages of the intrusions in the Ikerasassuaq area are known, since they are not in contact with those in the two other areas (see Pulvertaft 1977). Porphyritic granites on Sannerut have no mutual contacts with the Borgs Havn granites and may be older than indicated (syn-D1/D2 or older). Arrows indicate the relative timing of magmatic and high temperature solid-state deformation in each pluton.
* denotes sample collected for zircon geochronology.

The third phase of deformation (D3) is highly localised and was only recognised at a few localities. In the Sannerut area, a well-spaced D3 crenulation cleavage has a consistent anticlockwise trend relative to the main D2 deformation. Further south, emplacement of the Sâtukujoq granite during D3 was associated with a 2 km wide zone of intense dextral, non-coaxial deformation that transposed the early fabrics in the Nivâk granite. Strong prolate fabrics are locally developed in the Sâtukujoq granite together with flattening fabrics in the host Nivâk granite. The West Sánerut granite and some members of the porphyritic granite suite (see Fig. 5) were emplaced during this stage. The names of individual granite plutons follow Pulvertaft (1977) and do not exactly correspond to modern spelling of locality names (Fig. 1).

Preliminary and tentative conclusions

The Ketilidian structures between Midternæs and Qoornoq were formed during three successive phases of deformation within a complicated transpressive system. Upright folds (which in Midternæs refold earlier folds and were designated F2 by Higgins 1970) indicate NNW–SSE shortening in Midternæs and north-east Grænseland, whereas prominent D1 folds further south in Grænseland are consistent with thrusting of the Ketilidian cover rocks from north-east to south-west and also suggest significant sinistral displacements between Arsuk Bræ and Blindtarmen (Fig. 4). Southwest vergence of D2 folds in Grænseland suggests that thrust detachment continued in the cover rocks after D1 displacements. The deformation on Arsuk Ø took place during two main events and, according to earlier workers (see Berthelsen & Henriksen 1975), appears to have involved significant deformation of the surrounding Archaean basement. There appears to be no simple correlation of the history of deformation with that between Midternæs and Qoornoq.

The Kobberminebugt area is part of the northern marginal zone of the Julianehåb batholith. The complex non-coaxial deformation history of the area is characterised by kinematic and strain partitioning, shear-sense reversals, and sequential pluton emplacement. Foliation is generally steep, strikes NE–SW, and has a gently to moderately plunging stretching lineation. At central Kobberminebugt, three phases of deformation with associated syntectonic intrusions were recognised in the Ketilidian supracrustal rocks. D1 structures show consistent dextral kinematics whose late stage effects controlled intrusion of the Borgs Havn granites. D2 structures formed during progressive sinistral transpression, synchronous with intrusion of the Nivâk granite. Localised dextral reactivation gave rise to D3 structures which coincided with emplacement of the Sâtukujoq granite. Available structural data suggest that the sinistral D2 phase of deformation in the Kobberminebugt area correlates with the D1 phase between Midternæs and Qoornoq, but a firm conclusion awaits the dating of individual granite plutons. Correlation with the structural evolution on Arsuk Ø is currently considered uncertain.

Windley (1991, p. 3; 1993) had previously described the Kobberminebugt shear zone as "a 15 km wide, ENE-trending, subvertical, high deformation zone, which separates terranes of totally different type", and argued that a major metamorphic break occurs across the shear zone. He proposed that the Kobberminebugt shear zone represents a major suture that joins the continental margin, shelf and foredeep succession to the north with an Andean-type magmatic arc to the south. Our observations do not support this interpretation but suggest that the Kobberminebugt shear zone developed *in situ* in the northern marginal zone of the Julianehåb batholith; this is supported by the presence on both sides of the shear zone of Ketilidian supracrustal rocks with lithologies resembling those in Midternæs and Grænseland (see e.g. Pulvertaft 1977, p. 26 ff), which are intruded by various members of the Julianehåb batholith. The Kobberminebugt shear zone is therefore a transpressive shear zone in which the oblique convergence vector has been partitioned into components that are orogen parallel and normal to the orogen.

In conclusion, the border zone in the north-west of the Ketilidian orogen appears to represent a back-arc in which the foreland Archaean gneisses and Ketilidian basic volcanic and sedimentary rocks were affected by Ketilidian deformation, metamorphism and granite intrusion. The ongoing dating programme and geochemical study of the basic magmatism are designed to throw further light on this tentative conclusion. The results of the 1997 field work are compatible with the plate-tectonic model of Chadwick & Garde (1996) in which the Julianehåb batholith is viewed as the root zone of a major Palaeoproterozoic magmatic arc above a northerly dipping subduction zone at the southern margin of the Archaean craton.

Acknowledgements

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North-East Greenland 1997–1998: a new 1:500 000 mapping project in the Caledonian fold belt (72°–75°N)

Niels Henriksen

The Geological Survey of Denmark and Greenland (GEUS) continued in 1997 the systematic geological mapping programme for the 1:500 000 regional map series, with initiation of field work on sheet no. 11, which covers part of North-East Greenland. Of the 14 planned map sheets at 1:500 000 which will cover all of Greenland, 11 have been published, and one additional sheet for which field work has been completed is under compilation. Only two areas of Greenland are not yet covered by map sheets of this series: part of North-West Greenland (sheet no 6) and the target for the present project in North-East Greenland (sheet no. 11). The field work for the latter sheet is planned for two seasons, with the first season completed in 1997 and the second and final season to follow in 1998.

The map sheet (no. 11) covers the region between Kong Oscar Fjord and the Stauning Alper in the south (72°N) and Kuhn Ø and Grandjean Fjord in the north (75°N, Fig. 1). The western part of this region is dominated by crystalline complexes of the East Greenland Caledonian fold belt. A post-Caledonian sequence of Upper Palaeozoic and Mesozoic sediments and Tertiary plateau basalts and intrusions covers the eastern part of the region. This article focuses on the Caledonian geology, whereas results from the work in the post-Caledonian sediments are described in the article by Stemmerik *et al.* (1998, this volume).

The new Survey work for map sheet 11 represents a reinvestigation of areas extensively studied by geologists of Lauge Koch's expeditions to East Greenland (1926–58), the principal results of which were compiled by John Haller for the 1:250 000 map sheets covering the region 72°–76°N (Koch & Haller 1971) and incorporated into an impressive regional description of the East Greenland Caledonides (Haller 1971).

The Scoresby Sund region to the south of latitude 72°N and the Dove Bugt region to the north of latitude 75°N have already been investigated by the Geological Survey of Greenland (Henriksen 1986, 1997; Higgins 1994) as part of the present ongoing 1:500 000 regional mapping programme. The 1997–1998 mapping project will fill the last remaining gap in the Survey's 1:500 000 coverage of North-East Greenland.

All of North-East Greenland is covered by a set of wide angle black and white vertical aerial photographs taken in the period 1978–87 from an altitude of *c.* 14 km. On the basis of these aerial photographs and ground control points established by Kort- og Matrikelstyrelsen (National Survey and Cadastre – formerly the Geodetic Institute), new topographical maps of the entire region 72°–75°N, at a scale of 1:100 000, with 100 m contours, are being drawn at the Survey and will serve as a basis for the field investigations and the subsequent geological map compilations. Drawing of the topographic maps in the Survey´s photogrammetric laboratory is combined with photogeological interpretation both prior to and following the field investigations.

In addition to establishing a general overview of the regional geology, the project includes activities aimed at supplementing knowledge of the economic potential of the region, in respect to both minerals (Harpøth *et al.*1986) and hydrocarbons (Christiansen *et al.* 1992; Stemmerik *et al.* 1997). The field work co-ordinated by the Survey included co-operation with a geophysicist from the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, who undertook rock magnetic investigations to facilitate interpretation of an AWI aeromagnetic survey, and four Norwegian sedimentologists from Saga Petroleum whose work was integrated with a Survey group working with Mesozoic sediments (Stemmerik *et al.* 1998, this volume). Logistic support was also given to three groups of geologists from the University of Oslo and three geologists from Massachussetts Institute of Technology, with whom agreements on scientific co-operation had been arranged in advance.

Some aspects of the project are based on funding from the Danish National Science Foundation and Carlsberg

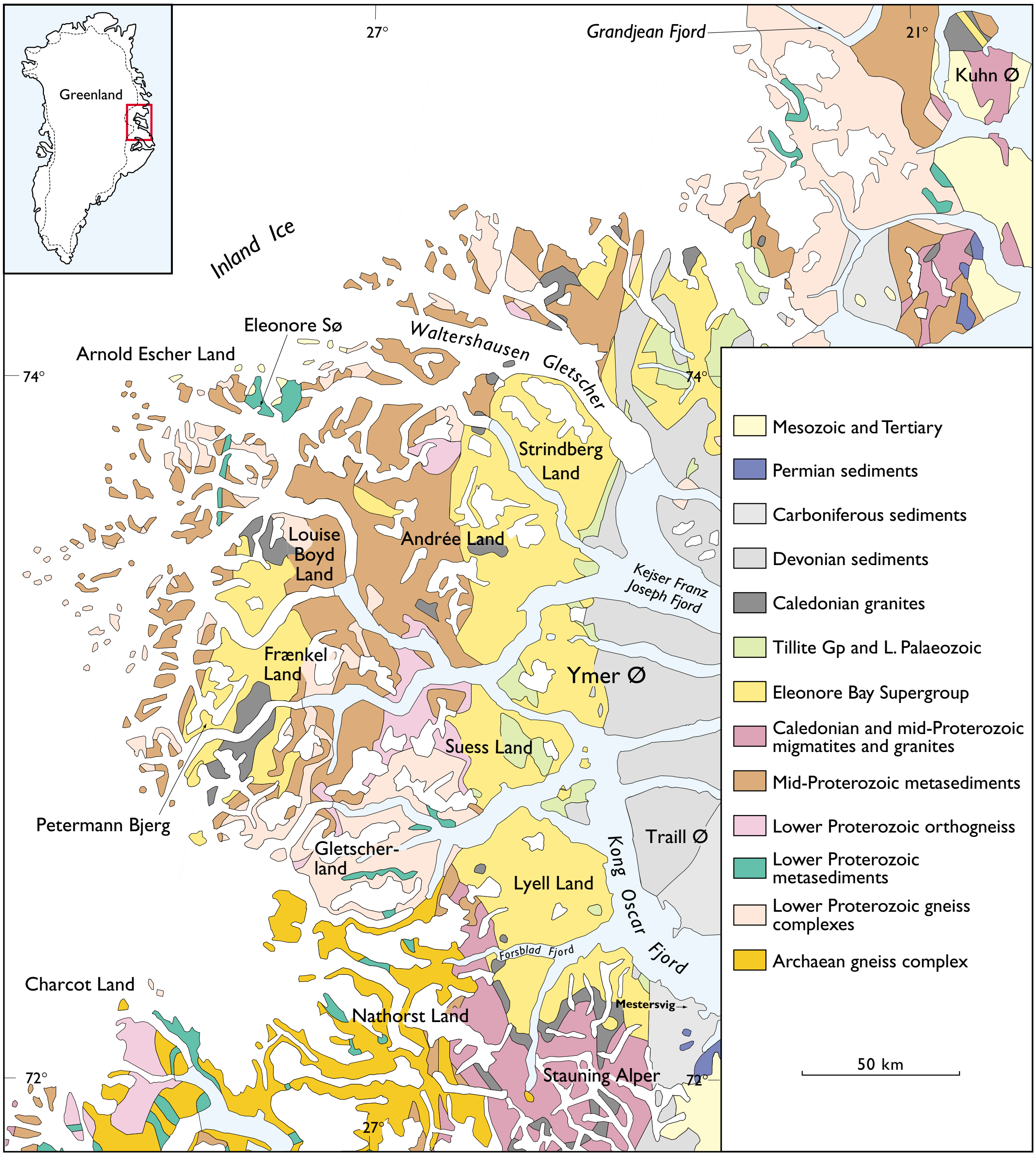


Fig. 1. Simplified geological map of the East Greenland Caledonian fold belt between 72° and 75°N. After Escher & Pulvertaft (1995).

Foundation, with support for special research topics concerning the pre-Caledonian basement terrain, Caledonian metamorphism, and studies of Upper Proterozoic carbonate sediments.

The field investigations in 1997 were carried out during a seven week field season between early July and late August with participation of a total of 38 persons, including 32 geologists (Henriksen 1998). The work was supported by two helicopters and a small, fixed wing, Twin Otter aircraft, which operated from Mestersvig, a former airport which is kept open for limited special operations by the military sledge patrol Sirius. The GEUS

Fig. 2. Stauning Alper with summits reaching almost 3000 m with a relief of 1500 m. View from the north.

group benefitted substantially from base facilities at Mestersvig, organised and manned by the Danish Polar Center (DPC). Transport between Mestersvig and Denmark was carried out by the Royal Danish Air Force (RDAF) using a C-130 Hercules aircraft.

Regional geological studies

The East Greenland Caledonian fold belt from 72° to 75° N comprises late Archaean and Proterozoic crystalline complexes which are tectonically overlain by a thick Upper Proterozoic (Eleonore Bay Supergroup) to Middle Ordovician sedimentary sequence. These units were subjected to large scale orogenic deformation and mountain building processes during the collision of Laurentia and Baltica following closure of the Iapetus Ocean (Harland & Gayer 1972; Henriksen 1985). The Lower Palaeozoic sediments contain ‘Pacific-type’ faunas indicating that East Greenland comprised part of the North American craton (Laurentia) prior to continental collision. Devonian – Lower Permian, late orogenic, continental sedimentary sequences were deposited in local intramontane basins during the late extensional phases of the Caledonian orogeny.

The classic interpretation of the East Greenland Caledonides erected by John Haller (1971) and coworkers envisaged the fold belt to be composed of two main structural levels (stockwerke); an upper suprastructural level of low grade to non-metamorphic sedimentary rocks with N–S trending, upright, open to gentle folds, and a lower infrastructural level dominated by intensely deformed gneisses, schists and granitoid rocks, generally metamorphosed to amphibolite facies grade. According to John Haller´s interpretation the rock units of both structural levels were correlatives, the infracrustal units being metamorphosed and gneissified equivalents of the overlying sediments. Later work, and notably isotopic age determinations have, however, demonstrated that the infrastructural levels comprise polymetamorphic Precambrian basement complexes which preserve evidence of three orogenic events prior to Caledonian reworking – late Archaean (3000 Ma), lower Proterozoic (1800–2000 Ma) and middle Proterozoic (*c.* 1000 Ma; Steiger *et al.* 1979; Henriksen 1985).

Large scale west-directed thrust nappes have previously been described from both the Scoresby Sund region to the south as well as from the northern part of the East Greenland Caledonides (Hurst *et al.* 1985; Henriksen 1986; Strachan *et al.* 1994), but had not hitherto been proven from the central part of the East Greenland Caledonides. In the summer of 1997, however, evidence was found to demonstrate that this region (72°–75°N) is also built up of major thrust and nappe sequences (see below).

The terrain of this part of North-East Greenland is characterised by a rugged alpine topography with mountain summits reaching almost 3000 m in the Stauning Alper (Fig. 2) and Petermann Bjerg regions. Wide fjord and glacier valley systems with steep walls and general E–W trends, transect the region approximately perpendicular to the main trend of the Caledonian fold belt (Fig. 3). Numerous local ice caps and glaciers are pre-

Fig. 3. Nordenskiöld Gletscher occupies a deep trough eroded into crystalline basement complexes. The steep walls and exposures are typical for the inner fjord zone. Summits reach 2300 m in altitude and about 1200 m above the glacier.

sent, and towards the west merge with the Inland Ice; a broad border zone of the Inland Ice is characterised by the occurrence of numerous nunataks. Except for some valley areas, vegetation is sparse and exposure is therefore generally very good.

Field work in 1997 covered, in addition to general mapping, most aspects of the regional geology in the Caledonian fold belt. The main projects included:

1. Pre-Caledonian basement in the crystalline complexes – a study using radiometric age determination methods;
2. Structure and lithostratigraphy of the crystalline complexes;
3. Metamorphic studies of Caledonian infracrustal and supracrustal units;
4. Granites in the fold belt – their relative and absolute age, geochemistry and plate tectonic setting;
5. Migmatisation processes and mechanisms, with studies of partial melting and emplacement patterns;
6. Sedimentology and basin analytical studies of the carbonate sediments in the Upper Proterozoic Andrée Land Group (Eleonore Bay Supergroup);
7. Mineral resource investigations in the basement crystalline complexes associated with major tectonic lineaments;
8. Magnetic susceptibility in the crystalline complexes of the southern part of the investigated region (72°–73°N); an AWI project.

Preliminary results of the field work have been summarised by the participating geoscientists in a volume of the Survey's Rapport series (Higgins & Frederiksen 1998), which forms the basis for the following presentation.

Crystalline complexes

The crystalline basement complexes within the East Greenland Caledonides are segments of the Precambrian Greenland shield (part of the North American Laurentian shield), which have been reactivated during the Caledonian orogeny. These complexes are dominated by polyphase orthogneisses, foliated granites and migmatites interbanded or overlain by sequences of paragneisses, amphibolites and metasediments (psammitic, pelitic and calcareous). The oldest complexes, which have yielded Archaean isotopic ages, are found in the southern part of the region and are most likely to be a northerly extension of the *c.* 3000 million year old Flyverfjord infracrustal complex of the Scoresby Sund region south of 72°N (Rex & Gledhill 1974). The gneisses of these complexes are characterised by abundant, cross-cutting, basic dykes and sills, which when deformed by later events occur as pods, lenses, layers and bodies of amphibolite (Fig. 4). Middle Proterozoic complexes are found in the Charcot Land tectonic window in the south-western part of the region, where a thick sequence of metasedimentary and metavolcanic rocks (Steck 1971) overlying an older gneissic basement is intruded by Middle Proterozoic granites (*c.* 1850 Ma old).

Quartzofeldspathic intrusive bodies of similar age are also represented in the crystalline basement complexes elsewhere in the region between 72° and 75° N; a number of granites and gneisses have given isotopic ages of *c.* 1700–2000 million years (Rex & Gledhill 1981). Throughout the region the infracrustal parts of the basement complexes are interleaved or overlain by a several kilometres thick sequence of metasedimentary rocks (psammitic and pelitic) now occurring as amphibolite facies schists and paragneisses, in places invaded by granitic sheets and bodies. Rb-Sr errorchron ages of *c.* 1000 Ma (Rex & Gledhill 1981), suggest a correlation with the Krummedal supracrustal sequence of the Scoresby Sund region farther south (Higgins 1988). However, the results of the 1997 field investigations indicate that there may be several different Proterozoic sedimentary sequences, although the dominant structures developed in these supracrustal rocks seem to be Caledonian (Leslie & Higgins 1998; Escher & Jones 1998). The unravelment of the geological development and composition of the crystalline basement complexes is an important goal for the present project, and four teams are involved with regional studies of structural, metamorphic, lithological and isotopic aspects of the problem (Elvevold & Gilotti 1998; Escher & Jones 1998; Friderichsen & Thrane 1998; Leslie & Higgins 1998). The contribution of K. Thrane is undertaken as a Ph.D. research topic.

Studies of the metamorphic evolution have focused on east–west transects across the fold belt. The boundary between the non-metamorphic or very low grade Upper Proterozoic Eleonore Bay Supergroup and the structurally underlying crystalline complexes is marked by a prominent east-dipping extensional detachment zone; it is possible that parts of this zone had an early compressional history. Metasedimentary sequences in the footwall of the detachment are amphibolite facies kyanite or sillimanite bearing schists and paragneisses; these may or may not be correlatives to the non-metamorphic to greenschist facies quartzites and banded pelites and sempelites which occur in the hanging wall of the detachment zone. Similar studies in the nunatak region to the west of a transition between the Upper Proterozoic Petermann Bjerg Group (Eleonore Bay Supergroup) and underlying high grade crystalline complexes have been interpreted as reflecting two phases of Caledonian metamorphism; an early phase of kyanite grade metamorphism associated with migmatisation was succeeded by a later phase associated with formation of extensional detachment zones which now separate high level and deeper seated parts of the fold belt (Escher & Jones 1998). Metamorphic pressure-temperature-time data will be integrated with a structural analysis in order to understand the tectonic evolution, and will involve studies of phase equilibrium, mineral zoning and geothermometry in the rocks.

Fig. 4. The oldest parts of the crystalline basement complexes within the East Greenland Caledonides have yielded Archaean radiometric ages of *c.* 3000 Ma. Veined orthogneisses are injected by later cross-cutting basic dykes which have been metamorphosed and recrystallised under amphibolite facies conditions. Tærskeldal, south-west of Forsblad Fjord. Person as scale.

Granites are abundant throughout the region, as components of the crystalline complexes and as discrete or diffuse intrusive bodies emplaced into Middle and Late Proterozoic metasediments. It is only when the granites invade the Upper Proterozoic Eleonore Bay Supergroup that they can clearly be identified as Caledonian. Geochronological and (isotope-) geochemical investigations of the granites have been undertaken by H.F. Jepsen and F. Kalsbeek. Field interpretations enable distinction of various deformed and undeformed granites of Caledonian age emplaced into Eleonore Bay Supergroup sediments (Fig. 5), as well as lithologically similar granites emplaced in other metasediments which

Fig. 5. Leucocratic Caledonian granite cutting recumbent fold in Upper Proterozoic Eleonore Bay Supergroup sediments. Grejsdalen, Andrée Land. The profile is approximately 700 m high.
Photo: Feiko Kalsbeek.

may be older. Jepsen & Kalsbeek (1998) suggest that granite formation may have taken place by partial melting of the metasedimentary sequences. The close spatial relationship between granites and metasediments, and the absence of lithologically similar granites in the gneissic basement complexes, is taken as strong evidence that all Caledonian granites were formed by anatexis and that they were not derived from melts at depth.

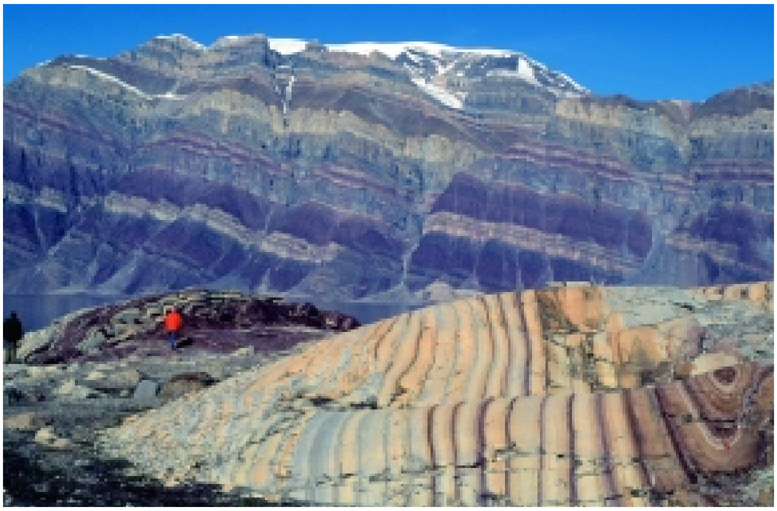
Migmatisation processes, due to partial melting of existing rock units during Caledonian or older orogenic events, are a prominent feature in the study region, and a special research project focused on this problem was organised in collaboration with Gordon R. Watt (Watt & Kinny 1998) with support from the Australian Research Council. The field aspect of the project involves mapping and logging of migmatites in an attempt to trace the introduced granite (neosome phase) from their site of formation to emplacement levels. This will be supplemented by geochemical and geochronological studies to determine the influence of melt-extraction mechanisms on melt chemistry and granite segregation processes. The migmatisation studies were mainly carried out in Nathorst Land and in the Stauning Alper, where distinction may be possible between migmatites of Caledonian age and possibly older but comparable migmatites. SHRIMP analysis on zircon concentrates will illuminate those questions which could not be solved on field criteria alone. It is expected to obtain a fuller appreciation of how granites are formed, how they migrate from their melting sites and ascend through the crust, and the factors which control their emplacement and final geometry.

Caledonian thrusts and foreland windows

The field studies in the nunatak region between 73° and 74°N have provided convincing evidence for the existence of large scale westwards directed Caledonian thrust sheets and nappes (Escher & Jones 1998; Leslie & Higgins 1998). This evidence, together with data from other regions, implies that major compressional tectonic events led to a thickening of the crust during the early phase of the Caledonian orogeny. Subsequent later phases encompass various transverse structures (Escher & Jones 1998) and the formation of the post-Caledonian basins (Hartz & Andresen 1995), and were related to extensional collapse and thinning of the crust.

The volcano-sedimentary complex of the Eleonore Sø region, Arnold Escher Land, was first described by Katz (1952) who presumed a correlation with the Eleonore Bay Supergroup. The 'Slottet Quartzite', which overlies the Eleonore Sø volcano-sedimentary complex, was in 1997 (Leslie & Higgins 1998) found to have a basal unconformable contact (not a thrust contact as originally described) and to preserve *in situ Scolithus* trace fossils indicating correlation with similar quartzites elsewhere in northern East Greenland and an uppermost Proterozoic to lowest Cambrian age (Sønderholm & Jepsen 1991; Strachan *et al.* 1994). The succession in Arnold Escher Land outcrops beneath a broad arched roof thrust transporting granite-veined and sheeted

Fig. 6. Exposures of part of the Ymer Ø Group and Andrée Land Group (Eleonore Bay Supergroup) in Forsblad Fjord. Berzelius Bjerg on the north side of the fjord is about 1900 m high.



metasediments to the north-west. There is a pronounced metamorphic contrast between hanging and footwalls of the thrust, which must be Caledonian in age. However, the footwall Eleonore Sø sequence carries the full sequence of Caledonian fold phases, and is thus provisionally interpreted as parautochthonous rather than autochthonous Caledonian foreland.

Other research topics

A sedimentological and stratigraphic basin analysis of the Upper Proterozoic Andrée Land Group (the former 'Limestone–Dolomite Series') of the Eleonore Bay Supergroup (Fig. 6) was undertaken as a Ph.D. research topic. Six profiles through the Andrée Land Group between Strindberg Land in the north and Scoresby Land in the south, were studied in detail (Frederiksen & Craig 1998). At each locality the succession was logged in detail to establish sedimentary facies divisions. The Andrée Land Group was found to be up to 1300 m in thickness and comprises a range of limestones and dolomites which can be divided into seven formations. The field work shows that they were deposited in a carbonate ramp system setting, with a steepened ramp towards the deep sea to the east and with a sheltered inner lagoon behind an inner, shallow barrier or shoal. The vertical sedimentary development of all sections shows a large-scale deepening upwards trend. The sedimentary, tectonic and climatic development will be analysed in terms of the sequence stratigraphic concept.

The nunatak zone north-west of inner Kejser Franz Joseph Fjord was known to preserve outcrops of Tertiary alkaline mafic lavas (Katz 1952; Brooks *et al.* 1979). In 1997 several new examples of Tertiary volcanic necks or plugs were discovered in the same region, some of which contain small mantle nodules (Leslie & Higgins 1998).

Mineral resource investigations were carried out in 1997 in the crystalline complexes between Andrée Land (73°30′N) and Lyell Land (72°30′N). Attention was focused on major tectonic lineaments, and in particular along the detachment zone between the Eleonore Bay Supergroup to the east and the underlying crystalline metamorphic complexes to the west (Stendal & Wendorff 1998). The detachment zone is a semi-brittle N–S trending, late Caledonian extensional fault zone, and can be traced for more than 100 km. Other geological settings investigated included various vein-related mineralisations in granite, aplite and pegmatite veins in the metamorphosed supracrustal sequences, and associated with Caledonian intrusives. More than 250 samples were collected (stream sediments, heavy mineral concentrates, grab and chip samples), and the results of the analyses will provide an evaluation of the mineral potential in the investigated area.

Since 1990 the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven has undertaken extensive airborne and shipborne magnetic and seismic investigations in order to investigate the crustal structure of East Greenland. As a follow-up of this extensive programme a geophysicist from AWI joined the

GEUS group in 1997 to carry out *in situ* measurements of magnetic susceptibilities in the crystalline complexes between *c.* 72° and 73°N (Schlindwein 1998a). The magnetic properties of the rocks will be used as an aid to interpretation of the aeromagnetic data. Basement rocks generally have low susceptibilities, apart from three relatively late magnetite-bearing granites; the latter cut early structures, but were themselves partly deformed. Metasedimentary sequences interleaved with the crystalline basement rocks also have low susceptibilities, but highly magnetic units were encountered in some associations of amphibolites, schists and marbles. Although less than one kilometre across, the magnetite-bearing granites are revealed on the aeromagnetic data as pronounced positive magnetic anomalies (Schlindwein 1998b). In general the aeromagnetic patterns and the ground susceptibility measurements help to distinguish crystalline complexes with different petro-magmatic evolution, and in this way contribute to understanding of the general geological development of the region.

Co-operation with other institutions

As noted above, the long term close co-operation between the Survey and AWI was continued in 1997 with a programme of ground magnetic susceptibility measurements. Scientific and logistical co-operation was also established with a group of geologists from the University of Oslo, Norway who have worked for several years in the Caledonian fold belt in the region north of Mestersvig. Their project has focused on the formation of late- to post-Caledonian extensional structures both in the crystalline complexes and in relation to the formation of the Devonian sedimentary basins. This group included a party from Massachussetts Institute of Technology (MIT), Cambridge, USA, studying the structural and metamorphic evolution of a late Caledonian detachment zone in the Forsblad Fjord area. Another group from the University of Oslo was given limited logistic support in their studies of the structures and emplacement of Tertiary sills in the Mesozoic sediments around Kong Oscar Fjord.

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The oldest marine Cretaceous sediments in West Greenland (Umiivik-1 borehole) – record of the Cenomanian–Turonian Anoxic Event?

Gregers Dam, Henrik Nøhr-Hansen, Flemming G. Christiansen, Jørgen A. Bojesen-Koefoed and Troels Laier

The stratigraphic borehole Umiivik-1 on Svartenhuk Halvø was drilled in August–September 1995 as part of a joint programme between the Government of Greenland, Minerals Office (*now* Bureau of Minerals and Petroleum) and the Danish State (Mineral Resources Administration for Greenland). The joint programme was based on a political decision from November 1994 made in order to attract the oil and mineral industry to Greenland. The drilling of Umiivik-1 is one of several petroleum geological projects in West Greenland that were initiated early in 1995. Analyses on the core include detailed sedimentological, palynological and organic geochemical studies. The other petroleum geological projects comprise: description and interpretation of the three exploration boreholes on Nuussuaq, GANT#1, GANE#1 and GANK#1 that the Canadian oil company grønArctic Energy Inc. drilled in the summer of 1995 (e.g. Christiansen *et al.* 1996a, c; Dam 1996a–c; Nøhr-Hansen 1997a); seismic surveys in the fjords around Disko, Nuussuaq and Svartenhuk Halvø (FjordSeis 95); seismic surveys in the offshore area between 68° and 71°N (DiskoSeis 95); and seismic surveys in the offshore area south of 68°N (IkerSeis 95, KangaSeis 95 and ExtraSeis 95; Chalmers *et al.* 1998, this volume; Skaarup & Chalmers 1998, this volume).

The prime objective of Umiivik-1 was to document oil-prone source rocks in mid-Cretaceous strata. Although several types of crude oil have been found in seeps and slim-hole cores in West Greenland since 1992, there was only limited knowledge on actual source rocks when the project was initiated. Detailed organic geochemistry, especially the distribution of biomarkers in seeping oils, provides important information on the type of organic material, the depositional environment and the thermal history of the source rocks that generated these oils (Christiansen *et al.* 1996b, 1997b; Bojesen-Koefoed *et al.* in press). However, there are only limited data on thickness, areal distribution, generative potential, and stratigraphic age of the actual source rocks. Considering the exploration possibilities in West Greenland, the presence of source rocks seems to be one of the main risk elements, if not the most critical factor. It was therefore generally accepted in 1994 that the level of exploration interest in West Greenland would strongly benefit from the actual demonstration of the existence, age and depositional environment of oil-prone source rocks and by quantifying their generation potential. The most likely candidate in this context was a possible mid-Cretaceous marine source rock (Cenomanian–Turonian) that was first suggested in West Greenland by Chalmers *et al.* (1993) on the basis of world-wide analogies, but later supported by direct data from Ellesmere Island in Arctic Canada (Núñez-Betelu 1994).

The Svartenhuk Halvø area is one of the few areas where Upper Cretaceous and Lower Tertiary marine sediments are exposed onshore West Greenland (Fig. 1), and the mudstones outcropping on Svartenhuk Halvø are the oldest known, fully marine deposits from West Greenland (Birkelund 1965; Nøhr-Hansen 1996). These mudstones have recently been studied during field work by the Geological Survey of Greenland in 1991 and 1992, a programme which also included five shallow boreholes between 66 and 86 m deep (Fig. 1; Christiansen 1993; Christiansen *et al.* 1994). Based on analytical work from these cores and samples from nearby outcrops, thermally immature mudstones of Coniacian to Early Santonian age have been documented (Nøhr-Hansen 1996), thereby giving hope that immature or early mature sediments of Cenomanian–Turonian age could be reached by drilling to relatively shallow depths along the southern shoreline of Umiiviup Kangerlua (Fig. 1).

Drilling project

The Umiivik-1 borehole is located on the southern coast of the bay Umiiviup Kangerlua, Svartenhuk Halvø

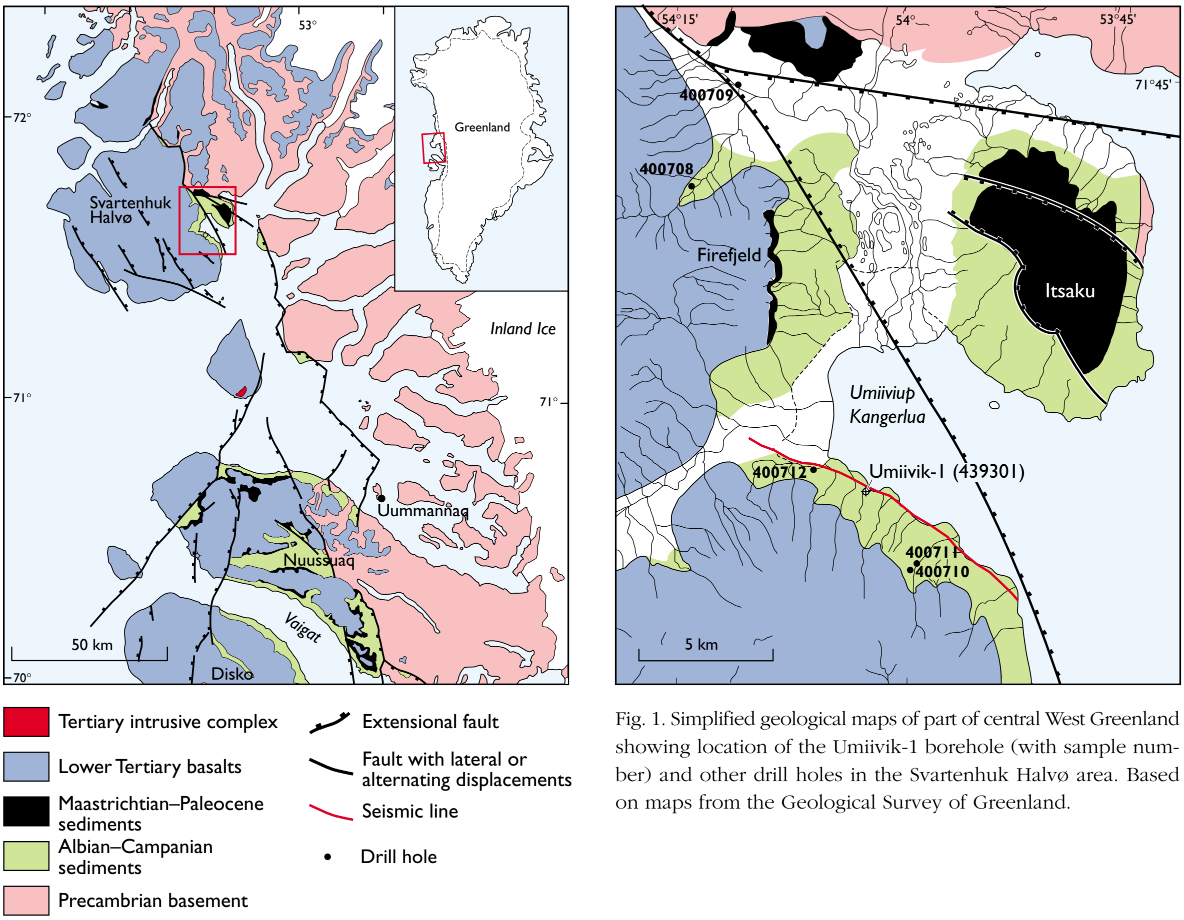


Fig. 1. Simplified geological maps of part of central West Greenland showing location of the Umiivik-1 borehole (with sample number) and other drill holes in the Svartenhuk Halvø area. Based on maps from the Geological Survey of Greenland.

(Fig. 1). The drill site was selected on the basis of a single 11.5 km long refraction and reflection seismic line acquired in the summer of 1994 (Christiansen *et al.* 1995; Fig. 1). The actual drilling position is close to shot point 86 on seismic line GGU SV94–01 in an area with a presumed large thickness of marine mudstones (Bate & Christiansen 1996). The drill site is 500 m inland from the coast at an elevation of approximately 5 m above mean sea level at the position 71°36′42″N, 54°02′31″ W.

Operational services were undertaken by grønArctic Energy Inc. on a 'turn-key' contract with the Government of Greenland, Minerals Office. The Geological Survey of Denmark and Greenland (GEUS) was responsible for selecting the drill site and performing all drill site geological services. This included a preliminary geological description of the core and collection of various types of samples (Bate 1996). Detailed organic geochemical, sedimentological and palynological studies have subsequently been carried out at GEUS, where the core is now stored (Christiansen *et al.* 1997b; Dam 1997; Nøhr-Hansen 1997b).

Technical details of Umiivik-1 are given in the well completion report by Bate (1996) which includes a preliminary geological log, description of penetrated lithologies, sample lists and information on hydrocarbon shows. Preliminary results and the geological background for the drilling programme have been summarised by Bate & Christiansen (1996). A total of 1200 m of core (GGU 439301) was drilled in Umiivik-1 in the period from 21 August to 13 September, 1995. The recovery was close to 100% with a core diameter of 63.5 mm in the uppermost 148 m of the hole and 47.6 mm in the remaining part. Almost the entire core consists of Upper Cretaceous marine mudstones cut by Paleocene dolerite intrusions (Fig. 2). The mudstones are dark grey with

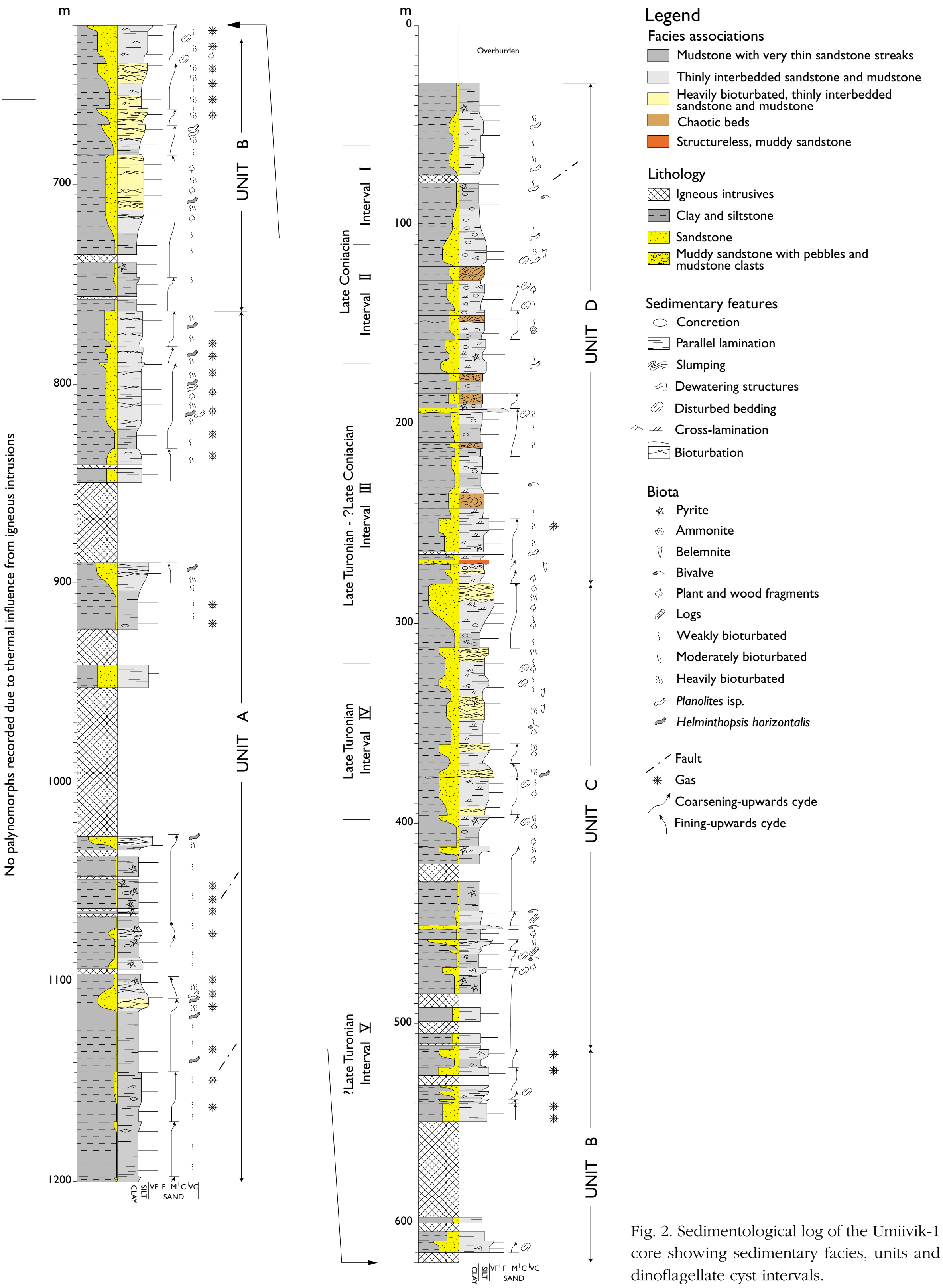


Fig. 2. Sedimentological log of the Umiivik-1 core showing sedimentary facies, units and dinoflagellate cyst intervals.

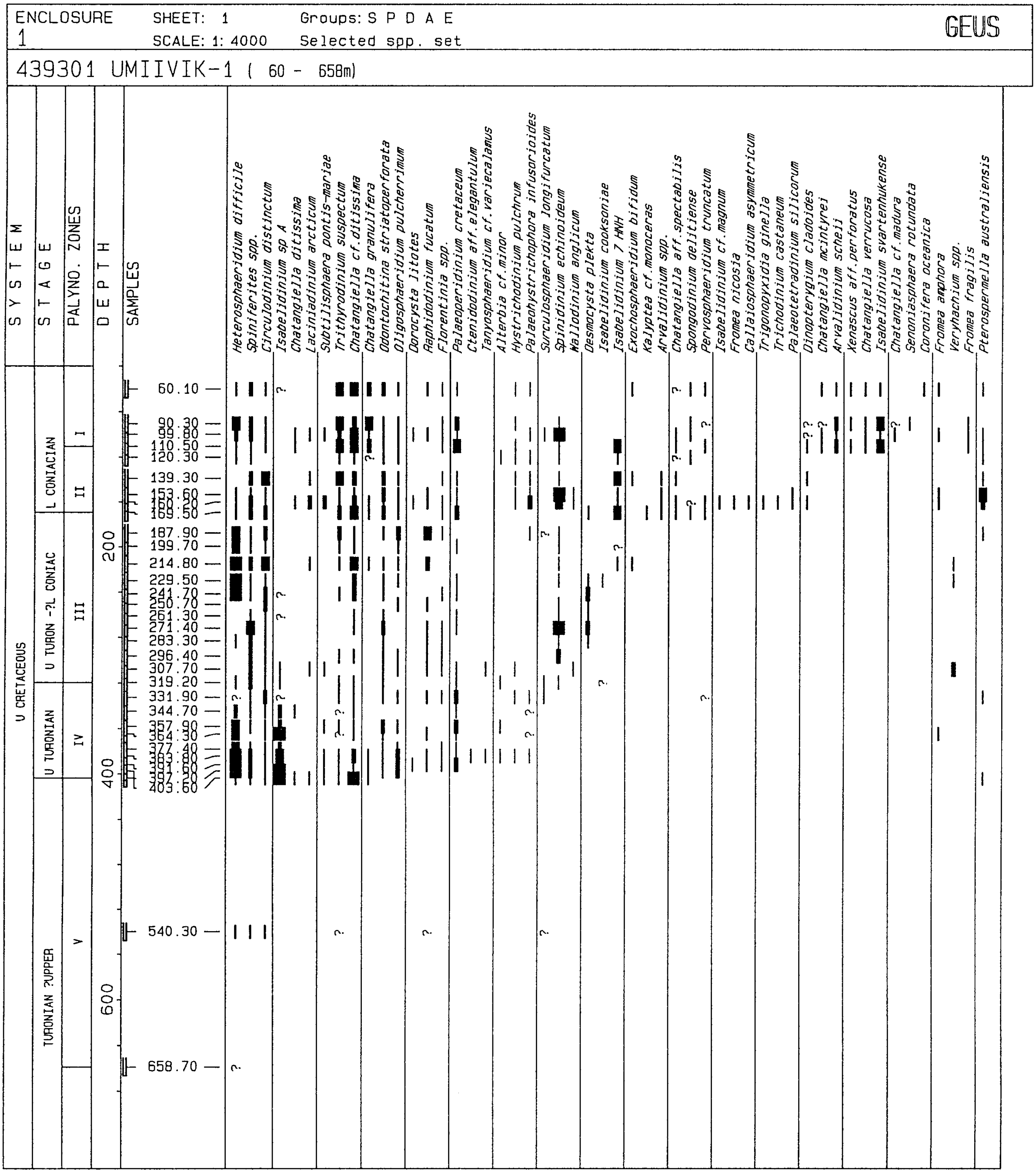
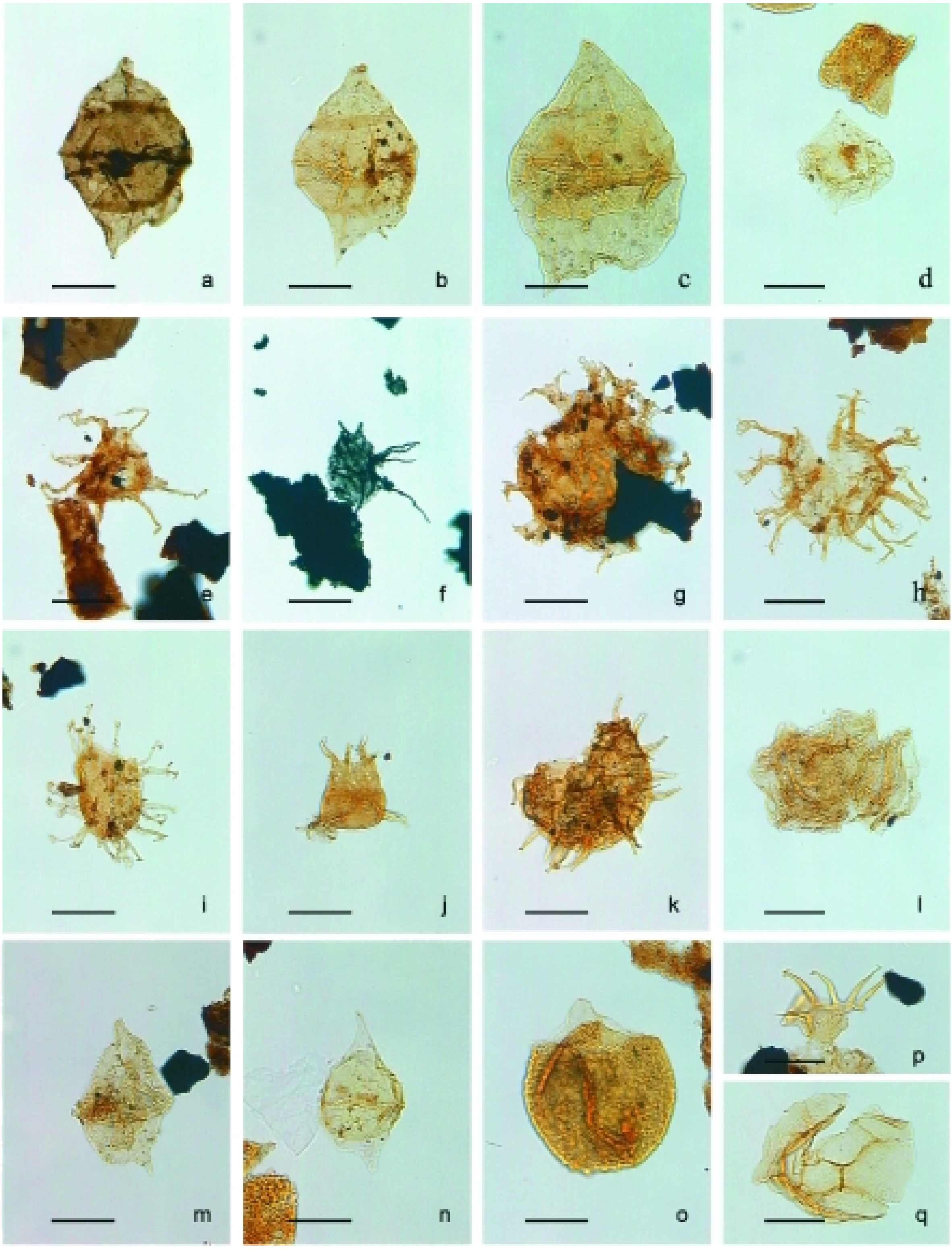


Fig. 3. Range chart of selected palynomorphs from the Umiivik-1 borehole, with division of the core into five dinoflagellate cyst intervals.

abundant silty interbeds and only a few sandstone intervals are present. A total of 22 dolerite intrusions with a cumulative thickness of 240.2 m were intersected throughout the borehole. The thick intrusions from 548.6 to 596.9 m, from 849.1 m to 890.2 m, and from 923.4 m to 1027.1 m have severely altered the marine mudstones, and have thereby limited the possibilities for both detailed organic geochemical and palynological studies in the deeper part of the borehole.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Palynostratigraphy

The dinoflagellate cyst stratigraphy of the Umiivik-1 borehole is based on a study of material from 36 mudstone samples (Fig. 3), of which the lowermost four samples (below 658 m) were barren of dinoflagellate cysts due to severe thermal alteration from dolerite intrusions (Nøhr-Hansen 1997b). The stratigraphic range of selected dinoflagellate cysts is shown in Figure 3. Based on the stratigraphical important species (Fig. 4) the uppermost 658 m of the borehole has been dated as Late Turonian to Early Coniacian. It is divided into five informal dinoflagellate cyst intervals (Fig. 2, 3; Nøhr-Hansen 1997b), of which the uppermost two intervals can be correlated with previous studies on Svartenhuk Halvø (Nøhr-Hansen 1996, 1997b). Previous biostratigraphic studies of ammonites and dinoflagellate cysts from the Umiivik area dated the oldest deposits as Coniacian to Early Santonian (Birkelund 1965; Nøhr-Hansen, 1996). However, Nøhr-Hansen (1996) noted that a Late Turonian age of the sediments from two shallow cores (GGU 400709 and 400712; Fig. 1) could not be excluded.

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Fig. 4. Stratigraphically important species in the uppermost 658 m of the Umiivik-1 borehole. Bar scale is 20 μm.

a. *Isabelidinium* sp. A, MGUH 24558 from GGU 439301-116-8, 27.3–98.4; LVR 1.8255; MI 5978.

b. *Isabelidinium* sp. A., MGUH 24559 from GGU 439301-110-4, 51.5–103.7; LVR 1.8283; MI 6004.

c. *Isabelidinium* sp. cf. *I. magnum*, MGUH 24560 from GGU 439301-38-2, 22.5–110.1; LVR 1.8321; MI 6040.

d. *Alterbia* sp. cf. *A. minor*, MGUH 24561 from GGU 439301-38.2, 19.4–105.5; LVR 1.8323; MI 6042.

e. *Raphidodinium fucatum,* MGUH 24562 from GGU 439301-112-8, 40.5–98.0; LVR 1.8265; MI 5988.

f. ?*Raphidodinium fucatum,* MGUH 24563 from GGU 439301-160-3, 24.1–99.1; LVR 1.8250; MI 5973.

g. *Heterosphaeridium difficile,* MGUH 24564 from GGU 439301-112-8, 24.8–96.4; LVR 1.8263; MI 5986.

h. *Surculosphaeridium longifurcatum*, MGUH 24565 from GGU 439301-94-9, 45.3–103.6; LVR 1.8290; MI 6011.

i. *Tanyosphaeridium* sp. cf. *T. variecalamus,* MGUH 24566 from GGU 439301-110-2, 50.0–110.5; LVR 1.8282; MI 6003.

j. *Dorocysta litotes*, MGUH 24567 from GGU 439301-38-2, 31.6–108.5; LVR 1.8322; MI 6041.

k. *Pervosphaeridium truncatum*, MGUH 24568 from GGU 439301-41-4, 40.3–95.6; LVR 1.8302; MI 6023.

l. *Senoniasphaera rotundata,* MGUH 24569 from GGU 439301-15-3, 19.6–94.1; LVR 1.8368; MI 6085.

m. *Spinidinium echinoideum,* MGUH 24570 from GGU 439301-36-2, 20.0–102.6; LVR 1.8308; MI 6027.

n. *Subtilisphaera pontis-mariae,* MGUH 24571 from GGU 439301-38-4, 46.8–108.7; LVR 1.8339; MI 6057.

o. *Trithyrodinium suspectum*, MGUH 24572 from GGU 439301-38-4, 48.9–96.7; LVR 1.8342; MI 6059.

p. *Ctenidodinium* sp. aff. *C. elegantulum,* MGUH 24573 from GGU 439301- 110-4, 45.9–97.4; LVR 1.8280; MI 6001.

q. *Ctenidodinium* sp. aff. *C. elegantulum,* MGUH 24574 from GGU 439301- 110-3, 26.0–98.6; LVR 1.8277; MI 6000.

The dinoflagellate cyst assemblages from Umiivik-1 are characterised by a large number of specimens of *Chatangiella* and *Isabelidinium*. According to the literature the genus *Chatangiella* ranges from the Late Cenomanian to the Late Maastrichtian (Costa & Davey 1992). The presence of *Heterosphaeridium difficile* down to 540.3 m in Umiivik-1 indicates an Early Turonian to Early Santonian age according to e.g. Costa & Davey (1992), whereas Bell & Selnes (1997) suggest a first appearance datum (FAD) for *H. difficile* close to the Early to Middle Cenomanian boundary based on data from the Norwegian shelf. The possible presence of *Raphidodinium fucatum* down to 540.3 m dates the core as post-middle Middle Turonian according to Costa & Davey (1992) or post-early Late Turonian according to Foucher (1979). The presence of *Pervosphaeridium truncatum* in the uppermost part of the core suggests an age no younger than Early Coniacian.

The lowermost recorded dinoflagellate cyst from 658.7 m has been identified as a *Chatangiella* sp. suggesting a post-Middle Cenomanian age (Costa & Davey 1992). The core from 687.7 m to 1191.4 m does not contain preserved dinoflagellate cysts. Thus the succession between 60.1 m and 540.3 m represents a Late Turonian to Early Coniacian age.

Sedimentology

A detailed core description, based on measurement in scale 1:1000 has been given by Dam (1997). Five facies associations have been recognised (Fig. 2). These are: (1) mudstone with very thin sandstone streaks; (2) thinly interbedded sandstone and mudstone; (3) heavily bioturbated thinly interbedded sandstone and mudstone; (4) chaotic beds; and (5) structureless, muddy sandstone.

The former three facies associations dominate the succession. The mudstones of these facies associations were all deposited from low-velocity, low-density turbidite currents dominated by Bouma D and E intervals. The sandstone streaks, laminae and beds are interpreted as deposits of traction and fall-out processes associated with sedimentation from waning, low-density turbitite currents.

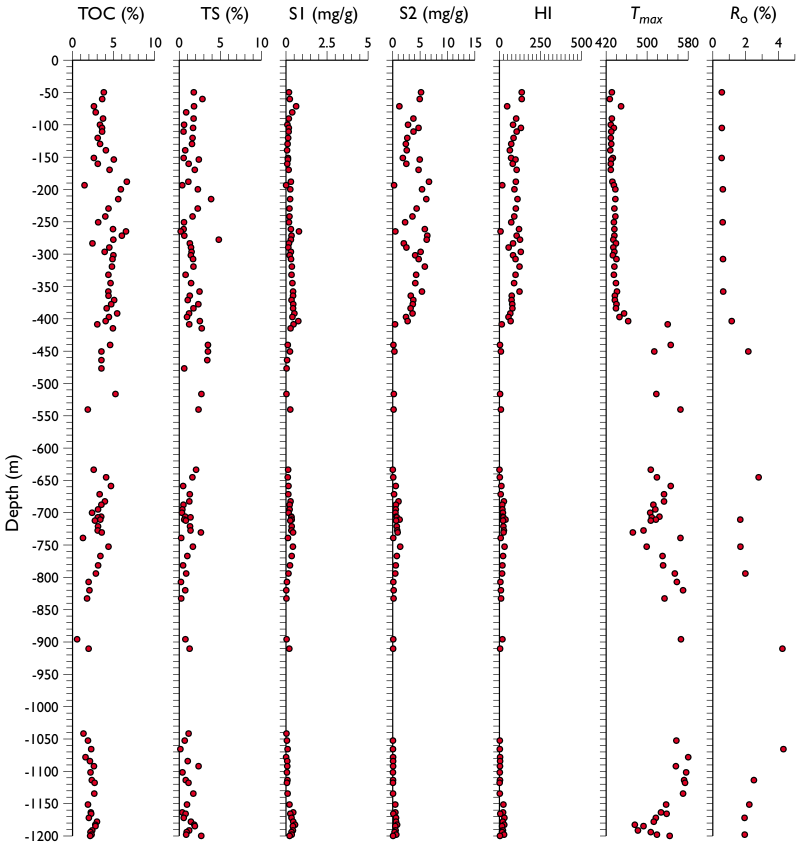

Fig. 5. Simplified geochemical log with LECO/Rval data (TOC, TS, S1, S2, HI, T_{max}) and vitrinite reflection data (R_o).

The trace fossils *Planolites* isp. and *Helminthopsis horizontalis*, and possible *Zoophycus* isp. and *Gyrochorte comosa*, have been recognised in the bioturbated intervals. The chaotic beds have only been recognised in the upper part of the core and consist of contorted beds of mudstone and thinly interbedded sandstone and mudstone of facies associations 1 and 2. The contorted bedding is attributed to slumping in an unstable slope environment. Structureless muddy sandstones deposited from sandy debris flows have only been recognised at one level in the upper part of the core. Dinoflagellate cyst assemblages, ammonites and belemnites, and the total sulphur content in the mudstones indicate a marine depositional environment for the complete cored succession.

Deposition of the Umiivik-1 sedimentary succession took place in the distal part of a major turbidite complex, probably the northern extension of the turbidite complex known from farther south in western and northern Nuussuaq (cf. Dam & Sønderholm 1994). The sedimentary succession is divided into four depositional units (Fig. 2; Dam 1997). The lower three units are 184 m to 295 m thick and show an overall thickening- and coarsening-upward trend interpreted as the result of progradation of the distal part of major submarine lobes. The overall coarsening-upward successions include well-developed coarsening-upward cycles 2–57 m thick. These are interpreted to represent smaller lobes formed in front of minor distributaries or as channel-levee-overbank complexes (Dam 1997). The uppermost Unit D is 247 m thick and differs from the three underlying units by the lack of an overall coarsening-upward trend, by the decrease in well-developed fining-upward cycles and the relatively large amount of slump deposits. The scarcity of systematic vertical variations in the thinly interbedded sandstone and mudstone of Unit D, suggests that these deposits were not confined to channel-levee systems, and that they more likely represent interchannel slope apron deposits. The increase of bioturbation from Unit A to Units B and C and the possible steepening of the slope, represented by the topmost Unit D, suggest that the cored succession in the Umiivik-1 borehole represents an overall progradation of a turbidite complex. However, the increase in slump and debris flow deposits may also suggest that the area became tectonically more unstable.

Organic geochemistry of mudstones

A standard analytical programme has been undertaken on the Umiivik-1 core (Christiansen *et al.* 1997) which included the following techniques: (1) LECO/Rock Eval pyrolysis (*n* = 98); (2) total sulphur analysis (*n* = 98); (3) vitrinite reflectance, R_o (*n* = 20); (4) extraction in a Soxtech apparatus with subsequent deasphalting and column separation into saturated and aromatic hydrocarbons and NSO compounds (*n* = 9); (5) analysis of saturated hydrocarbons by gas chromatography/mass spectrometry (GC/MS) (*n* = 9); (6) head space gas composition (*n* = 27), C isotopes of methane (*n* = 17), in some cases of ethane (*n* = 8) and propane (*n* = 6).

There is a significant difference in thermal maturity between the upper part of the core (above 390 m), and the deeper part below 405 m with only a thin transition zone. In the upper part T_{max} values range from 427°C to 441°C whereas vitrinite reflectance values range from 0.55% to 0.63% (Fig. 5). This suggests that the sediments are thermally immature or at a level corresponding to the early part of the oil window. In the lower part T_{max} values and vitrinite reflectance values are very high and seem to be controlled by the position of major intrusions.

The content of total organic carbon (TOC) of the mudstones is moderate to high with most values between 2% and 6% (Fig. 5). In the upper part, the Hydrogen Index (HI) varies from 63–136. These values suggest a poor to fair source rock potential for oil. In the lower post-mature part of the core HI values are typically below 25, in many cases below 10. Total sulphur values (TS) typically vary from 0.5% to 3.5% with a few very low and very high values. This range of values suggests a marine depositional environment for mudstones.

Due to the high thermal maturity below *c.* 405 m only nine mudstones from the upper part of the core were extracted and analysed by gas chromatography and gas chromatography/mass spectrometry. The analytical details and interpretations are given in the report by Christiansen *et al.* (1997b). All data from these samples are rather similar and suggest a significant input of terrestrial organic matter and a relatively low thermal maturity. The biomarker distributions show very low concentrations of angiosperm biomarkers and a notable concentration of bisnorhopane in several samples. This composition shows some similarities to the Itilli oil type described by Bojesen-Koefoed *et al.* (in press) and to the Kanguk Formation source rock from Ellesmere Island (Bojesen-Koefoed *et al.* 1997), although both the Itilli oil type source rock and the Kanguk source rock seem to have been deposited during more restricted conditions than the analysed sediments from Umiivik-1.

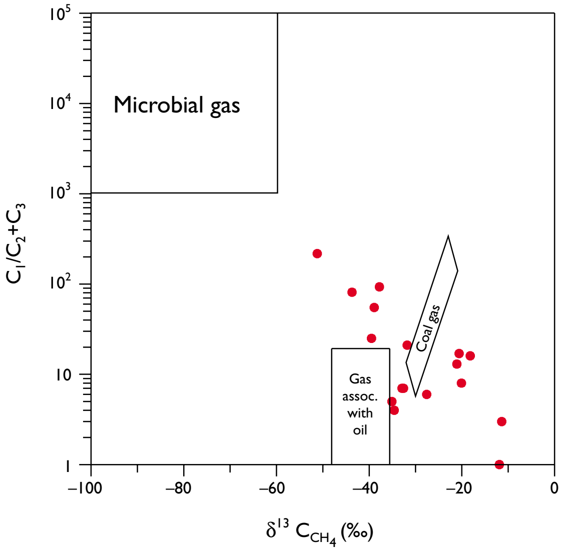

Fig. 6. $C_1/C_2 + C_3$ (= wetness) versus ^{13}C-isotope composition of methane.

Gas geochemistry

Head space analyses on cans containing core samples show that considerable quantities of gas were released from some intervals (Christiansen *et al.* 1997b). The highest recorded gas values are from the intervals 100–300 m and 1150–1200 m, but scattered high values have been recorded throughout the core. Methane is the most abundant hydrocarbon gas, the $C_1/C_2 + C_3$ ratio being 3 to 200 with a general decrease with depth. Samples from deeper than 794 m in particular are very wet ($C_1/C_2 + C_3$<10), and one interval from 1151 to 1182 m shows very high concentrations of wet gases (including both normal and isobutane and pentane).

The isotope composition of the gases varies considerably, especially for methane (Fig. 6), whereas the variation for ethane and propane is much smaller. These isotope values together with the often relatively high wetness are in accordance with a thermogenetic origin of the gases. Some of the samples have a composition typical of gas associated with oil, although the composition is clearly affected by diffusion (see details in Christiansen *et al.* 1997b).

Conclusions and recommendations for future work

Although Umiivik-1 did not give the ultimate break-through that was hoped for from this stratigraphic borehole, it has added important geological knowledge that will be useful in the evaluation of the exploration possibilities on- and offshore West Greenland in the future.

The Umiivik-1 borehole penetrated the oldest marine sediments recorded so far in West Greenland, and the documentation of a thick prograding turbidite complex at this time in the basin development has important implications for deposition of source rocks and reservoir sandstones in the Nuussuaq Basin, as well as in neighbouring offshore basins. The overall progradational trend of the turbidite complex and the presence of a thick mudstone unit at the base of the drilled succession with very high concentrations of wet gases, suggest that the lower mudstone unit represents a major condensed section. Although it has not been possible to date this mudstone due to the thermal influence from the nearby igneous intrusives, the presence of Upper Turonian strata *c.* 500 m above the mudstone might indicate that this is the interval which has been recognised as a world wide Cenomanian–Turonian Oceanic Anoxic Event (cf. Schlanger *et al.* 1987). This event occurs at the base of a highstand systems tract, and occupies a similar position in the Umiivik-1 borehole.

The palynological results obtained have extended the biostratigraphic correlation scheme into a considerably older succession than previously documented, results that will be important for correlation of future wells in West Greenland. The combination of palynostratigraphy and organic geochemistry of the marine mudstones in the upper part of the core has given good possibilities for correlating biomarker distributions with stratigraphic age, and thereby making correlations between seeping oils and presumed source rock intervals much more certain.

The organic geochemical results suggest the existence of a possible source rock for condensate, perhaps even oil, in the deeper part of Umiivik-1. Due to the high thermal maturity (late part of oil window – early part of gas window) this possible Cenomanian–Turonian source rock cannot be dated in detail and it is not possible to document the detailed composition of generation products and the generative potential.

The results are encouraging for further studies on Svartenhuk Halvø, especially after the discovery of oil seepage there in 1997 (see Christiansen *et al.* 1998, this volume). New drilling is risky and is not recommended without very careful planning of how intrusions can be avoided at an alternative drill site. Follow-up field work aiming at more detailed sedimentological and palynological studies of outcropping Upper Cretaceous sediments as well as systematic ‘oil hunting’ combined with structural studies may give the most likely break-through in coming years.

Acknowledgements

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The northernmost marine Cretaceous–Tertiary boundary section: Nuussuaq, West Greenland

Gregers Dam, Henrik Nøhr-Hansen and W. James Kennedy

A new northern high-latitude Cretaceous–Tertiary (K–T) boundary section has been studied at Annertuneq on the north coast of Nuussuaq, central West Greenland (Fig. 1). This boundary section (Fig. 2) is the northernmost marine boundary section recognised so far (placed at palaeolatitude 58°N by Smith *et al.* 1981) and has been studied with respect to palynology, palaeontology, sedimentology, rare earth elements, magnetic susceptibility and carbon isotopes in order to describe and provide the context for the marine floristic changes across the K–T boundary in high northern latitudes (Nøhr-Hansen & Dam 1997; Kennedy *et al.* in press). The present paper is a summary of a research project on the K–T boundary section at Annertuneq, supported by the Carlsberg Foundation.

The K–T boundary

Palynological data have provided critical evidence in testing the meteorite impact hypothesis of the terminal Cretaceous extinction event (Alvarez *et al.* 1980). This hypothesis has been in the forefront of the discussion in geology and palaeontology because of the change in palynomorphs and extinction of the dinosaurs, discovery of iridium enrichment and shocked quartz at K–T boundaries in North America and the presence of the postulated major meteorite crater in Chicxulub, Mexico (e.g. Alvarez *et al.* 1980; Nichols 1996). Alternatively, it has been suggested that sulphuric acid and volcanic dust from the Deccan Trap volcanism in India could have led to climatic deterioration causing the major extinction at the K–T boundary (e.g. Officer *et al.* 1987). The palynological record of the event and its effects on terrestrial plants and dinoflagellate cysts, as well as the association of palynomorphs with the iridium anomaly, have been described and summarised in several papers (e.g. Nichols 1996; Sweet *et al.* 1990; Moshkovitz & Habib 1993; Elliot *et al.* 1994; Brinkhuis & Schøiler 1996). Most of the K–T boundary sections occur in low and mid-palaeolatitudes. Studies on a large number of terrestrial mid- and high-northern localities in North America have been summarised by Nichols (1996) who concluded that the K–T boundary transition in high northern latitudes is complex and involved more than a single event and that extinctions were superimposed on floristic alterations already in progress due to various climatic and environmental fluctuations. In North America high-latitude marine Cretaceous–Tertiary sediments are known only from Bylot Island and Devon Island, Canadian Arctic Archipelago (Ioannides 1986), but unfortunately a major unconformity eliminates the K–T boundary there (Benham & Burden 1990).

The section at Annertuneq appears to be complete and therefore it provides important new information about the marine floristic changes across the boundary in high northern latitudes. Preliminary studies indicate that complete boundary sections may also occur at Kangilia and in the section penetrated by an exploration well (GRO#3; Fig. 1). However, palynomorph assemblages are not as well preserved there as at Annertuneq.

Geology at Annertuneq

The work of Birkelund (1965), Rosenkrantz (1970) and Hansen (1980) forms the basis of our knowledge of the stratigraphy on the north coast of Nuussuaq. However, during the Survey's petroleum geological studies onshore West Greenland since 1991 a number of detailed sections were measured at Annertuneq and Kangilia (Fig. 1). One result of these studies was a new detailed Upper Cretaceous palynostratigraphy for the north coast outcrops established by Nøhr-Hansen (1996). Rosenkrantz (1970) placed the Cretaceous–Tertiary boundary on Nuussuaq at an unconformity between the 'undifferentiated marine Cretaceous shales' and the

Geology of Greenland Survey Bulletin 180, 138–144 (1998)

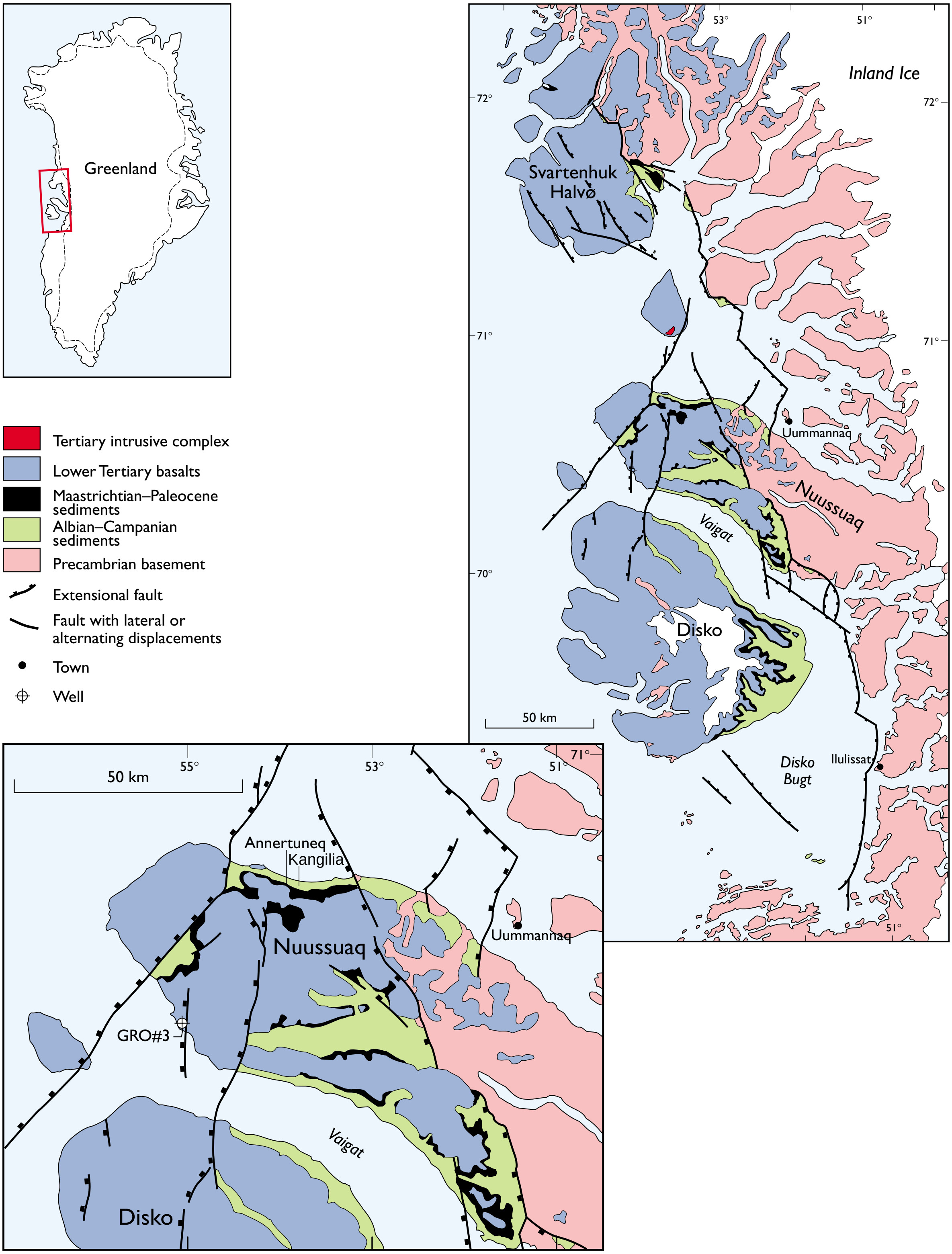

Fig. 1. Simplified geological map of West Greenland showing the Annertuneq locality. Based on published Survey maps.

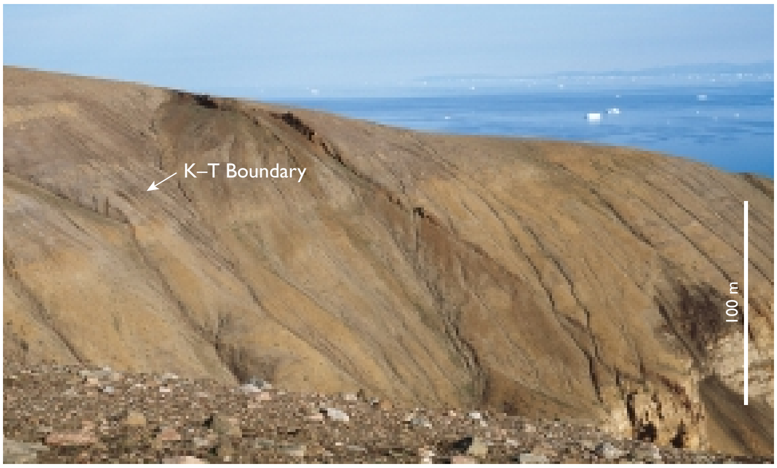

Fig. 2. The K–T boundary section at Annertuneq, Nuussuaq, central West Greenland.

‘Conglomerate Member’ at the base of the Kangilia Formation (Fig. 2) and it was believed that the K–T boundary strata were not preserved. However, during the Survey’s geological studies several loose fragments of ammonites were discovered above the ‘Conglomerate Member’ in small ravines in the neighbourhood of Annertuneq. In 1994 ammonites were found *in situ* in a concretionary layer *c.* 200 m above the base of the conglomerate (442 m a.s.l.). This locality was not recorded in the extensive work on the Late Cretaceous ammonites of West Greenland by Birkelund (1965). In 1995 the location was revisited, with financial support

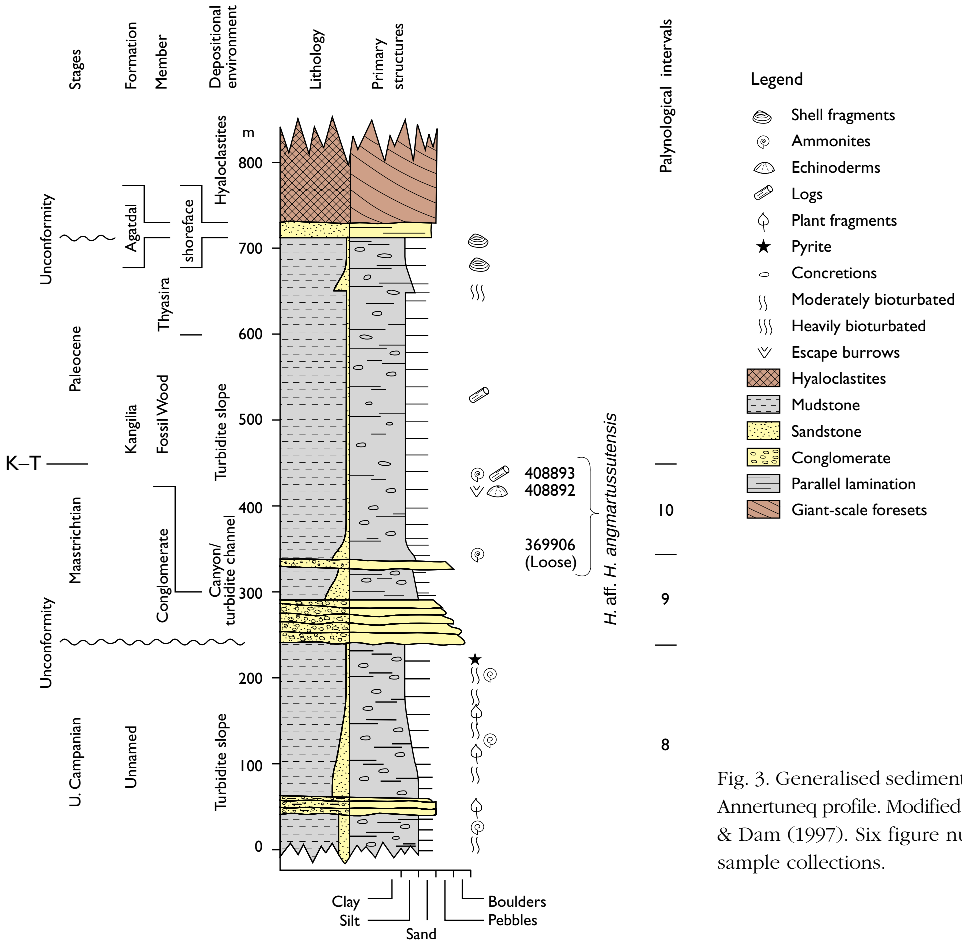

Fig. 3. Generalised sedimentological log of the Annertuneq profile. Modified from Nøhr-Hansen & Dam (1997). Six figure numbers are Survey sample collections.

from the Carlsberg Foundation, and the section was closely sampled in order to locate the K–T boundary.

The exposed sedimentary succession at Annertuneq is *c.* 725 m thick and consists of Upper Campanian to Paleocene turbidite slope and shoreface deposits (Fig. 2). Two tectonically controlled unconformities are present in the succession: at the base of the Upper Maastrichtian – lowermost Paleocene Kangilia Formation, which is marked by a submarine canyon conglomerate, and at the base of the shoreface sandstones of the Paleocene Agatdal Formation. The sedimentary succession is overlain by thick hyaloclastites and flood basalts. The K–T boundary is placed at 452 m above sea level in the Fossil Wood Member of the Kangilia Formation (Fig. 3). The Fossil Wood Member consists of mudstones interbedded with very thin and thinly bedded fine- to coarse-grained sandstones. Calcite concretions are common. The mudstones are poorly laminated, and some of the laminae appear to be graded. The sandstones have a sharp base and are usually normally graded. They are structureless or parallel laminated and escape burrows penetrate some of the sandstones. A 5 cm thick pebbly sandstone occurs just above the K–T boundary (Fig. 4). The pebbles consist of well-rounded quartzite clasts, less than 2 cm across.

Apart from *Teredo*-bored fossil wood, the Fossil Wood Member is poor in fossils. However, ammonites, echinoderms, and fossil wood are present in an *in situ* calcite concretionary layer, 25–30 cm thick, *c.* 10 m below the K–T boundary (Figs 3, 4).

The thinly interbedded sandstones and mudstones are interpreted as deposits of traction and fall-out processes associated with various stages of sedimentation from waning, low-density turbidity currents. Part of the mudstones may also have been deposited from suspension. The pebbly sandstone was deposited from sand- and pebble-rich turbidity currents. Deposition took place in a marine slope environment.

Ammonites

The ammonites collected at Annertuneq occur in loose concretions collected 50 m above the top of the conglomerate and *in situ* at 112 m above the conglomerate (10 m below the K–T boundary; Fig. 3; Kennedy *et al.* in press). All determinable specimens can be referred to what Birkelund (1965) called *S. (D.)* aff. *S. angmartussutensis*, referred to *Hoploscaphites* Nowak, 1911 by Kennedy *et al.* (in press). The relationship of the *H.* aff. *H. angmartussutensis* sequence to the dinoflagellate succession was refined by the examination of dinoflagellates from the matrix of additional identifiable ammonites. The specimen of *H.* aff. *H. angmartussutensis* collected loose from 50 m above the conglomerate at Annertuneq and those from 10 m below the K–T boundary, all yielded assemblages of the *Wodehouseia spinata* interval 10 of Nøhr-Hansen (1996) (Kennedy *et al.* in press). None of the material from the ammonites examined contain the dinoflagellates *Palynodinum grallator* or *Disphaerogena carposphaeropsis* which, according to Nøhr-Hansen & Dam (1997), represent the uppermost Maastrichtian in West Greenland. The affinities of the ammonite fauna do not indicate a link from West Greenland to the Western Interior of North America during the Maastrichtian; rather there are indications of an open marine link to the North Atlantic region.

Samples

Samples were collected at 10 cm intervals from 441.9 to 456.5 m above sea level and at 20 cm intervals from 427.2 to 441.6 m above sea level at Annertuneq (Figs 3, 4). All samples were analysed for their palynomorphs and magnetic susceptibility. Across the boundary, 20 samples were analysed for organic carbon isotopes and 30 samples for rare earth elements. All samples are stored at the Survey in Copenhagen, Denmark.

Palynology

The palynomorph assemblages place the K–T boundary at Annertuneq within a 10 cm interval between 451.9 and 452.0 m, just below a thin (5 cm) pebbly sandstone deposited from a turbidity current (Fig. 4; Nøhr-Hansen & Dam 1997). The late Maastrichtian assemblage is characterised by the presence of the dinoflagellate cysts *Laciniadinium arcticum*, *Isabelidinium majae*, *Palynodinium grallator*, *Disphaerogena carposphaeropsis*, and *Manumiella* spp. and the spores and pollen *Wodehouseia quadrispina*, *W. spinata*, *Aquilapollenites* aff. *A. spinulosus*, *Aquilapollenites* spp., *Striatocorpus* spp. and *Myrtipites scabratus* (Fig. 4). Three new species belonging to the genera *Striatocorpus* and *Aquilapollenites* have been recorded throughout the latest Maastrichtian deposits. One has affinities to the Paleocene species *Aquilapollenites spinulosus* and may be its latest Maastrichtian precursor. The earliest Danian

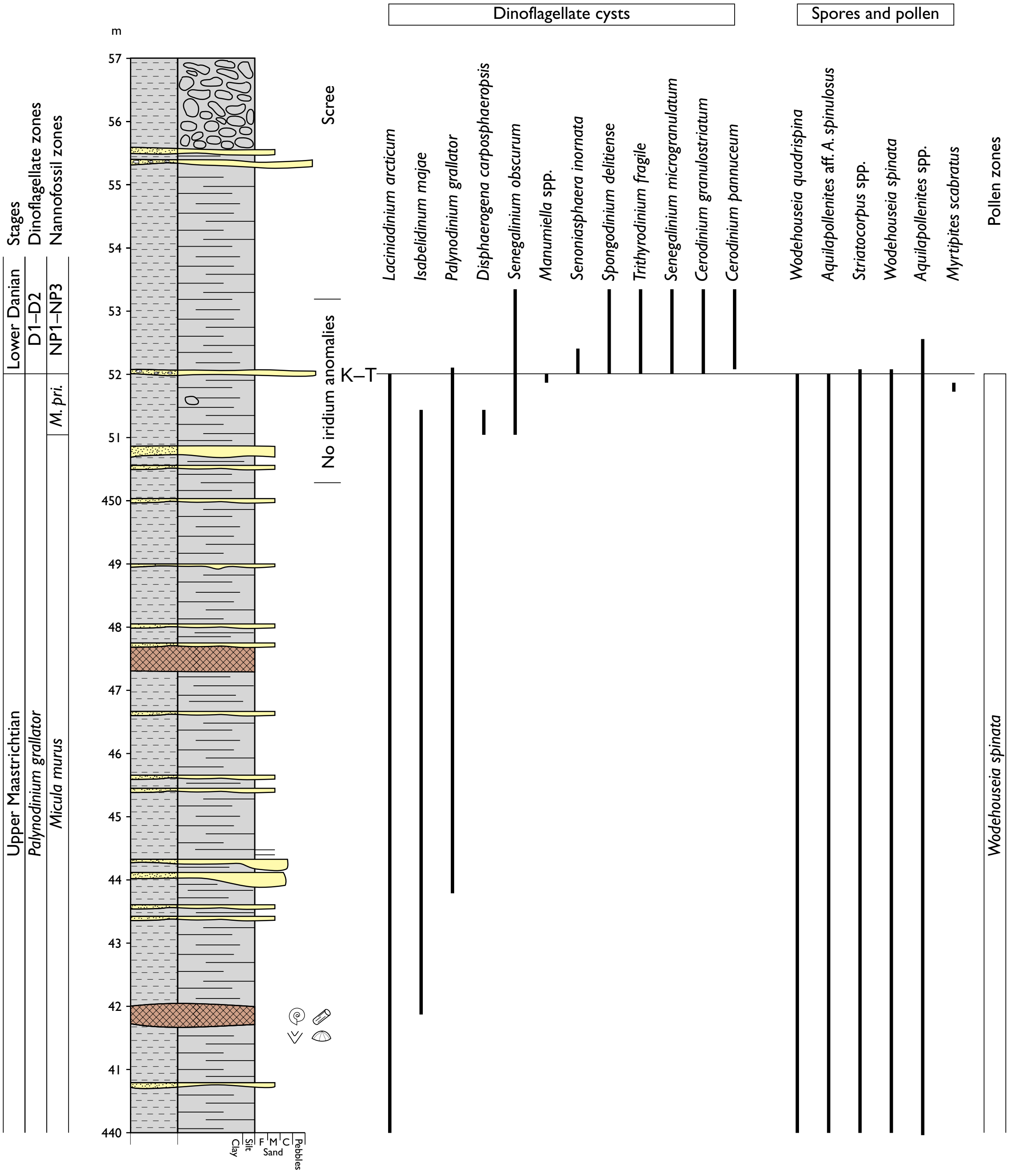

Fig. 4. Detailed sedimentological log and stratigraphic ranges of selected palynomorphs across the K–T boundary at Annertuneq. Modified from Nøhr-Hansen & Dam (1997). See Fig. 3 for legend.

assemblage is characterised by the first occurrence of the dinoflagellate cysts *Senoniasphaera inornata*, the abundance of *Spongodinium delitiense*, *Trithyrodinium fragile*, and *Senegalinium* spp., and by the disappearance of the pollen genera *Wodehouseia* and *Aquilapollenites* just above the boundary.

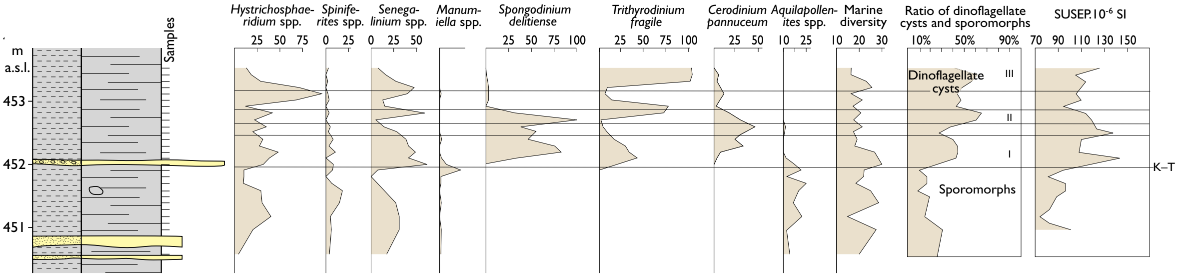

Fig. 5. Relative abundance (counted numbers) of selected palynomorphs, marine diversity (species richness), ratio of dinoflagellate cysts to sporomorphs (pollen and spores) and magnetic susceptiblity across the K–T boundary at Annertuneq. Modified from Nøhr-Hansen & Dam (1997). See Fig. 3 for legend.

Environmental interpretation

The composition of the palynomorph assemblages changes significantly across the boundary. Sporomorphs (spores and pollen) dominate the assemblage below the boundary (67–90%), whereas above the boundary the percentage of dinoflagellate cysts increases (28–65%; Fig. 5). The dominance of sporomorphs below the boundary is interpreted as the response to a regressive phase in the latest Cretaceous, whereas the observed increase in dinoflagellate cysts above suggests an earliest Danian transgressive phase (Nøhr-Hansen & Dam 1997). The transgressive phase was associated with an increase in supply of nutrients and increase in oceanic circulation or warming in the earliest Danian. This overall regressive-transgressive trend across the K–T boundary appears to be a world-wide event (e.g. Moshkovitz & Habib 1993; Elliot *et al.* 1994; Brinkhuis & Schiøler 1996).

The distinct fluctuations in the proportion of dinoflagellate cysts and sporomorphs in the lower Danian sediments are interpreted as reflecting three high-frequency transgressive-regressive cycles (Nøhr-Hansen & Dam 1997). The first transgressive phase (I, Fig. 5) began with a peak occurrence of *Senegalinium* species, suggesting a period of upwelling or flooding of major land areas that caused an increase in nutrient supply to the sea. As the transgression proceeded, a peak occurrence of *Trithyrodinium fragile* occurred that could mark the incoming of low- to mid-latitude species. The middle part of the first transgressive phase is characterised by a peak occurrence of *Spongodinium delitiense,* interpreted as indicative of oceanic conditions. In the second transgressive phase (II), the same three peak occurrences are recognised, but not in the same order. The third transgressive phase (III) is similar to the first phase, except that *S. delitiense* is missing. Within transgressive phases I and III, peaks in the marine diversity curve (at 452.1 m and 453.3 m) suggest two major flooding events.

The cyclic signals and the peak occurrences of selected dinoflagellate cyst species (Fig. 5) are not reflected in the sedimentology, but may reflect changes in sea level, palaeocurrents, or palaeoenvironment (Nøhr-Hansen & Dam 1997).

Magnetic susceptibility, rare earth analysis and carbon isotope stratigraphy

Magnetic susceptibilities were measured for all samples, using the method described by Hansen *et al.* (1993). Hansen *et al.* (1993, 1996) demonstrated that identical patterns in magnetic susceptibility versus stratigraphic depth can be recognised in Upper Cretaceous sedimentary successions separated by very large geographic distances.

The method was also applied to the West Greenland sample material and the results show characteristic shapes of the peaks for 500 000 and 400 000 years before the boundary (unpublished data), which seems to correlate with the shapes from the numerous boundary sections analysed by Hansen *et al.* (1993, 1996). The shape of the peak for 300 000 years before the boundary may perhaps be recognised, whereas it has not been possible to identify the peaks for 200 000 and 100 000 years before the boundary in the present material, suggesting that the deposits representing the last 200 000 years of the Maastrichtian stage may include minor hiati.

Thirty samples taken with 10 cm spacing across the K–T boundary were analysed for rare earth elements.

Iridium values range from 0.025 to 0.290 ppb, but no anomalies were recognised to support the hypothesis of a major meteorite impact with release of iridium on the earth. However, as the samples were taken with 10 cm spacing and without knowing the precise location of the biostratigraphic position of the K–T boundary during sampling, a possible iridium layer may have been missed and the analyses are thus regarded as inconclusive.

Studies of the K–T boundary sections at several localities have also shown a negative change in carbon-isotopic composition across the boundary (e.g. Hansen *et al.* 1996). Unpublished carbon-isotopic data from the K–T boundary at Annertuneq shows no such change in $\delta^{13}C$ values.

Selected samples analysed for calcareous nannofossils were all barren.

Acknowledgements

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Seismic investigations offshore South-East Greenland

John R. Hopper, Dan Lizarralde and Hans Christian Larsen

A high-resolution, shallow-seismic survey off the South-East Greenland coast was carried out during August and September 1997 aboard the R/V *Dana* of the Danish Ministry of Agriculture and Fisheries. This seismic survey supports two large ongoing regional research projects. The Danish Lithosphere Centre (DLC) is involved in a number of investigations to understand the tectonic evolution of the North Atlantic region since the early Tertiary, and a consortium of scientists from the Geological Survey of Denmark and Greenland (GEUS) and the Free University of Amsterdam (VU) are engaged in palaeo-oceanographic studies of climate change since the Neogene. The survey was thus a cooperative venture where ship time was shared between the participating research institutes. This report focuses on the DLC component of the cruise, which primarily involved the acquisition of site-survey data to be used in the planning and execution of drilling operations scheduled for 1998. These drilling operations are aimed at understanding the voluminous volcanic activity that accompanied continental rifting and the formation of the South-East Greenland margin. The GEUS/VU component of the cruise is summarised elsewhere in this volume (Kuijpers *et al.* 1998, this volume).

Background

The East Greenland margin is a type example of a volcanic rifted margin. These margins, which have now been identified in many parts of the world, are characterised by the emplacement of large volumes of volcanic rock during continental breakup and the onset of seafloor spreading (e.g. Coffin & Eldholm 1994). Thicknesses of new igneous crust on these margins can exceed 25 km, which is about three times the thickness of normal seafloor-spreading (oceanic) crust. It appears that most of the Atlantic margins north of *c.* 58°N are volcanic and that their formation is somehow related to the Iceland plume, which today is producing igneous crust up to four times the thickness of normal oceanic crust (Bjarnason *et al.* 1993; Reid *et al.* 1997). Many questions surround the role that the Iceland plume may or may not have had on rifting, breakup, and seafloor spreading in the area. DLC research in South-East Greenland should help to answer these questions and thus give insight into the links between lithospheric and crustal scale processes and the dynamics of the underlying asthenospheric mantle.

There are currently a number of interdisciplinary research programmes designed to address these problems. Crustal-scale seismic reflection and refraction experiments have been conducted to determine the thickness and seismic velocity of the crust along and across the margin, providing a regional view of the mass fluxes associated with margin formation (Dahl-Jensen *et al.* 1995; Holbrook *et al.* 1997). In addition, direct sampling of the basalt flows has provided geochemical constraints on the temperatures and pressures of melting and on the timing of distinct magmatic episodes (e.g. Larsen & Saunders 1998).

An important component of DLC's sampling programme is offshore drilling to sample the basalts extruded during the earliest stages of volcanic margin formation. The basalts were deposited subaerially as extensive flows that have since subsided and rotated seaward, giving them a characteristic appearance on seismic-reflection records as sequences of seaward-dipping reflectors. Ocean Drilling Program (ODP) Legs 152 and 163 targeted these basalts along two transects – EG63 near 63°N and EG66 near 66°N (Larsen *et al.* 1994; Duncan *et al.* 1996). Unfortunately, a severe hurricane during Leg 163 caused that cruise to be terminated nearly a month early, leaving a number of drilling objectives unfulfilled, including almost the entire EG66 transect. In the summer of 1998, a commercial drill ship chartered by the DLC will continue and expand upon the drilling programme begun by ODP. The primary purpose of the R/V *Dana* survey was to collect additional data in support of this new drilling initiative.

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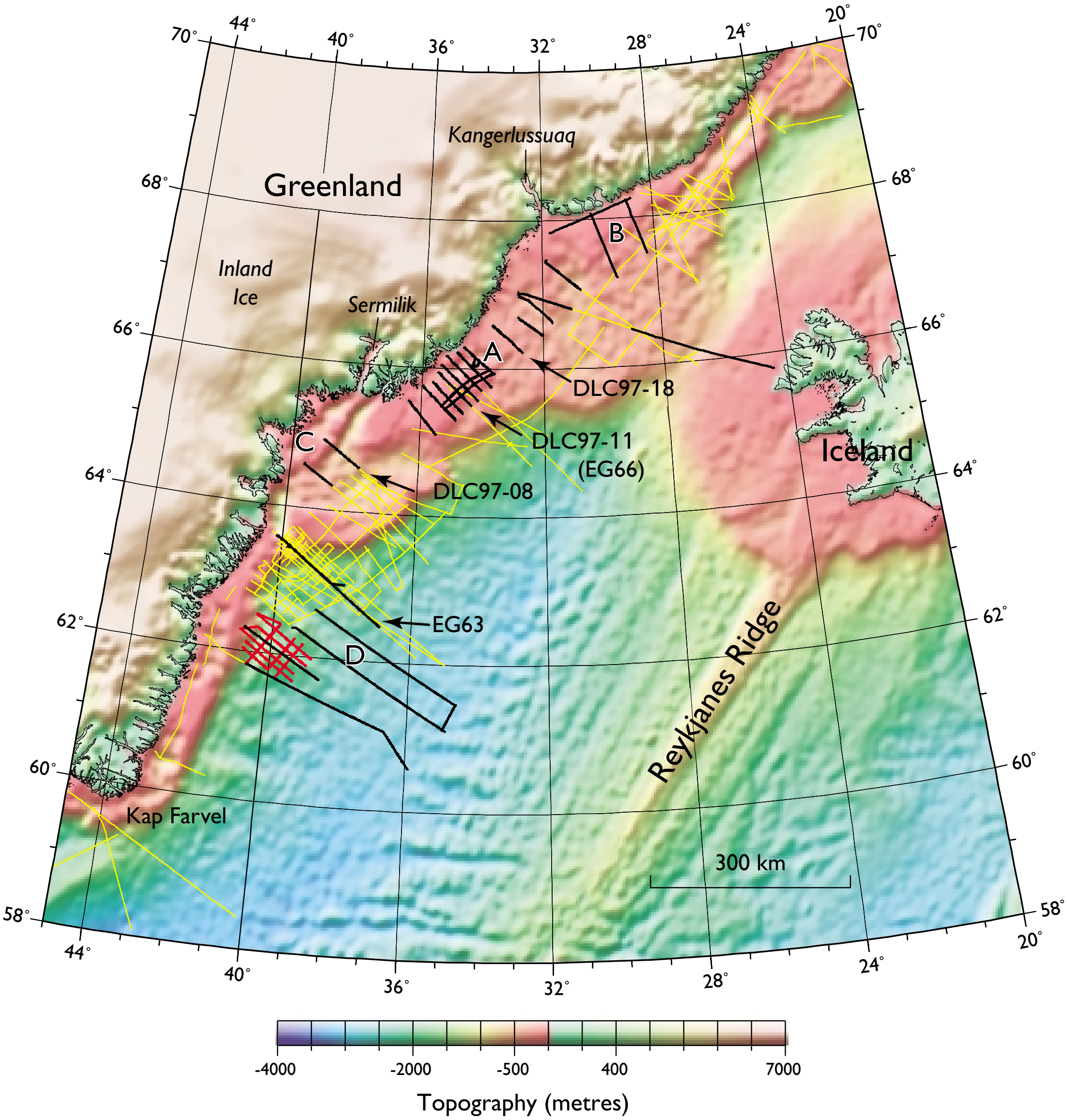

Fig. 1. Location map showing where new data were collected in 1997 on the R/V *Dana*. The thick black lines are data collected by the DLC and the red lines are data collected by GEUS and the Free University, Amsterdam. Tracks from previous seismic surveys are shown in yellow. Data from the lines labelled are shown in Figures 2, 3, 5. A, B, C and D are survey regions discussed in the text.

The R/V *Dana* Survey

On the 1997 R/V *Dana* cruise we acquired 3781 km of new, high-resolution seismic data during 34 days at sea. Of this, 3052 km were shot for the DLC work and 729 km were for the GEUS/VU project. We recorded only 35 hours of down time due to weather, ice and equipment problems. We used the new acquisition system recently purchased by the Geophysics Department at the University of Aarhus (AU), Denmark. This includes a 96 channel, 594 m hydrophone streamer with a 6.25 m channel interval and a Geometrics R48 recording system.

The airgun array consisted of 4 × 40 in^3 sleeve guns chained together in a cluster with a centre to centre spacing of 50 cm. Navigation was controlled by Navipac software and positioning was provided by an Ashtech GG24 receiver that uses both the United States global posi-

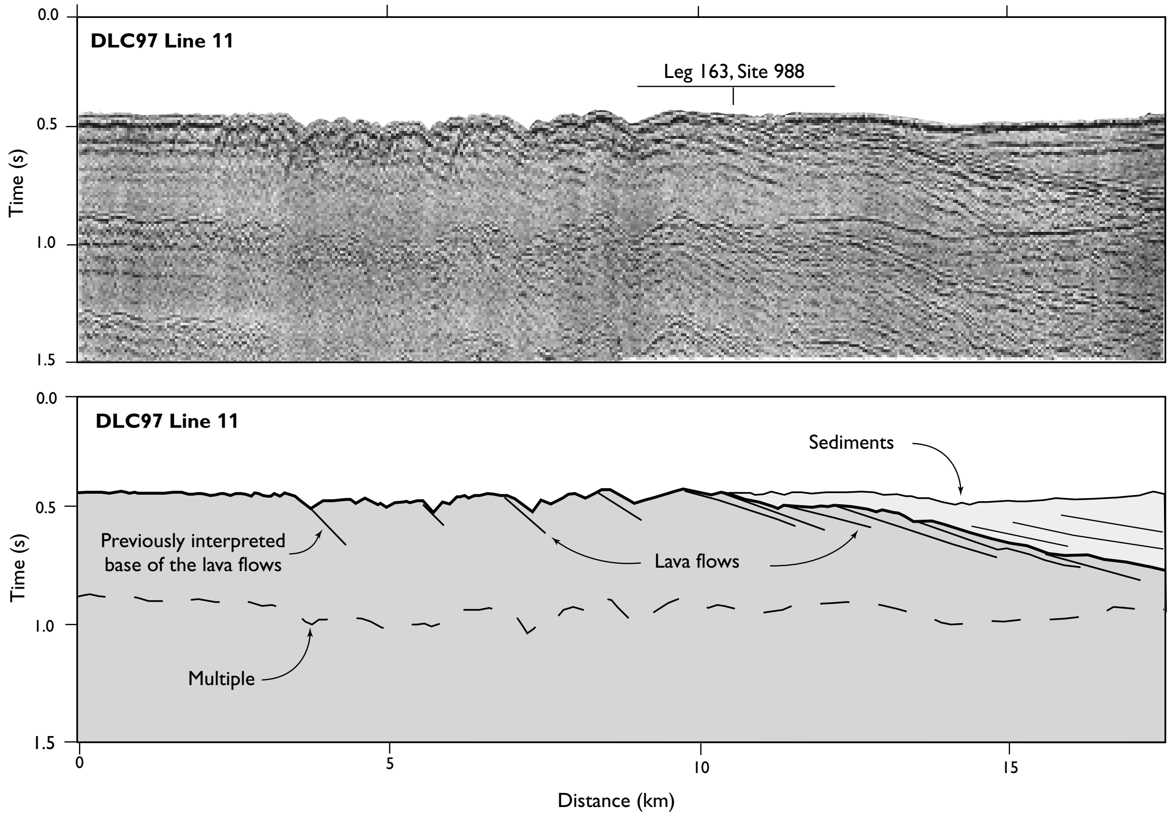

Fig. 2. Line DLC97-11, which coincides with the EG66 drilling transect. The top is the brute-stack produced on board and the bottom is a line drawing of the major features. The approximate location of site 988 from ODP Leg 163 is also shown.

tioning system (GPS) satellites and the Russian GLONASS satellites. As a backup, a second Ashtech GPS receiver recorded the raw GPS data for post-processing. For most of the survey, we also towed a Geometrics 866 marine magnetometer.

For the DLC part of the survey, seismic lines were shot in four main regions off the coast (Fig. 1). Region A is centred on the EG66 drilling transect and is the primary target area for the 1998 drilling. Region B lies offshore of the major DLC land-sampling and mapping areas (Larsen *et al.* 1995) and is close to the Greenland–Iceland Ridge, which is believed to be the hot spot track. Region C is an area that we hypothesised may be a zone of rifted continental crust inland of the seaward dipping reflectors. We shot two short lines to investigate this possibility. Region D includes a line shot over the EG63 drilling transect as well as several lines shot much farther out to sea. These latter lines were acquired to investigate the nature of the oceanic crust seaward of the volcanic margin. In this report, we discuss data from regions A and C and refer readers to the Cruise Report on file at the DLC for a more comprehensive description of the data collected (DLC 1997).

Region A

A dense grid of seismic lines was shot in region A, one of the primary target areas for the forthcoming 1998 drilling. Geochemical data suggest that a strong along-margin gradient in mantle source properties existed between Kangerlussuaq and the EG63 drilling transect at the time of margin formation (Fitton *et al.* 1997). Results of the 1996 deep seismic reflection and refraction work (SIGMA) also reveal a major change in the magmatic flux along the margin during breakup somewhere south of this region (Holbrook *et al.* 1997).

The uppermost crustal structure typical of this part of the margin is illustrated by line DLC97-11, which coincides with the EG66 drilling transect (Fig. 2). A well defined set of seaward dipping basalt flows crop out from beneath the sediment cover near km 10.5. The

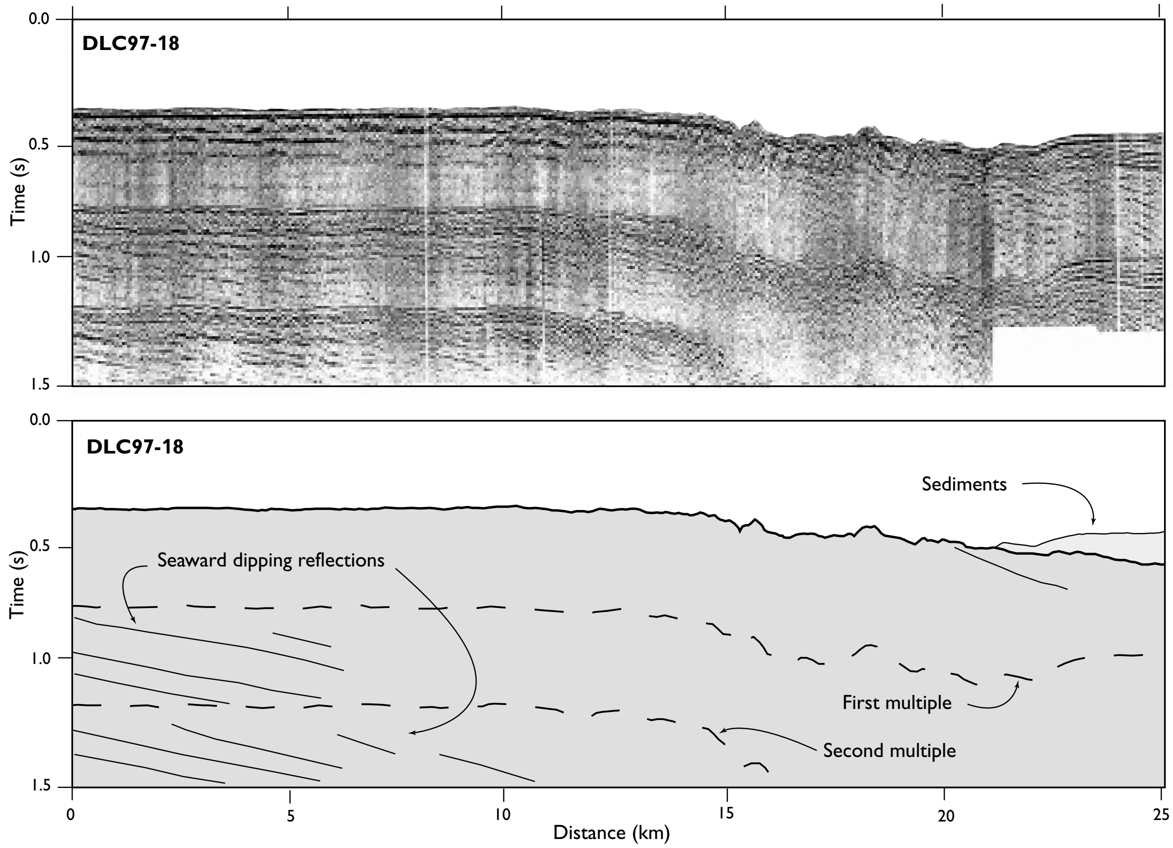

Fig. 3. Line DLC97-18, which is located farther north along the coast than the line DLC97-11 (Fig. 2). The data indicate that there may be seaward-dipping reflectors very similar to those produced by the basalt flows much farther landward than previously interpreted.

seafloor is very rough landward of this point, and this roughness probably represents the eroded edges of more seaward-dipping basalt flows. The seafloor becomes smooth again landward of km 2.5. This landward transition from rough to smooth had previously been interpreted as marking the base of the basalt flows deposited on continental crust (Duncan *et al.* 1996). This interpretation places one of the successful Leg 163 holes, Site 988 (Fig. 2), well within the main basalt flows. Thus, it was thought to be equivalent to either the pre-breakup lower series lavas or the breakup related upper series lavas, both of which are found on the EG63 transect. Those lavas are well constrained to be between 56 and 61 Ma (Sinton & Duncan 1998). Age determinations on volcanic material recovered from Site 988 have yielded much younger dates of 48 Ma (Tegner & Duncan in press), however, presenting an inconsistency that may call into question the regional chronological framework that needs to be tested with further drilling.

There are two likely explanations for the young age of the basalts recovered at Site 988. These rocks may have originated from late-stage, off-axis volcanoes situated on top of older basalts. However, the interpreted stratigraphic relations around the Site 988 basalts tend to argue against this explanation. It is also possible that the smooth to rough transition described above does not mark the landward edge of the base of the lava pile and that the basalts continue much farther landward, placing the Site 988 rocks higher in the stratigraphic column. This possibility is supported by evidence from the shipboard stack of line DLC97-18 (Fig. 3), where clear seaward-dipping reflectors are imaged in the first and second multiples. Similar events are observed on DLC97-13 (not shown). While further processing and analysis of the *Dana* data is necessary, we believe that these data and the new drilling results will show that the earliest basalts extend considerably farther landward than previously thought.

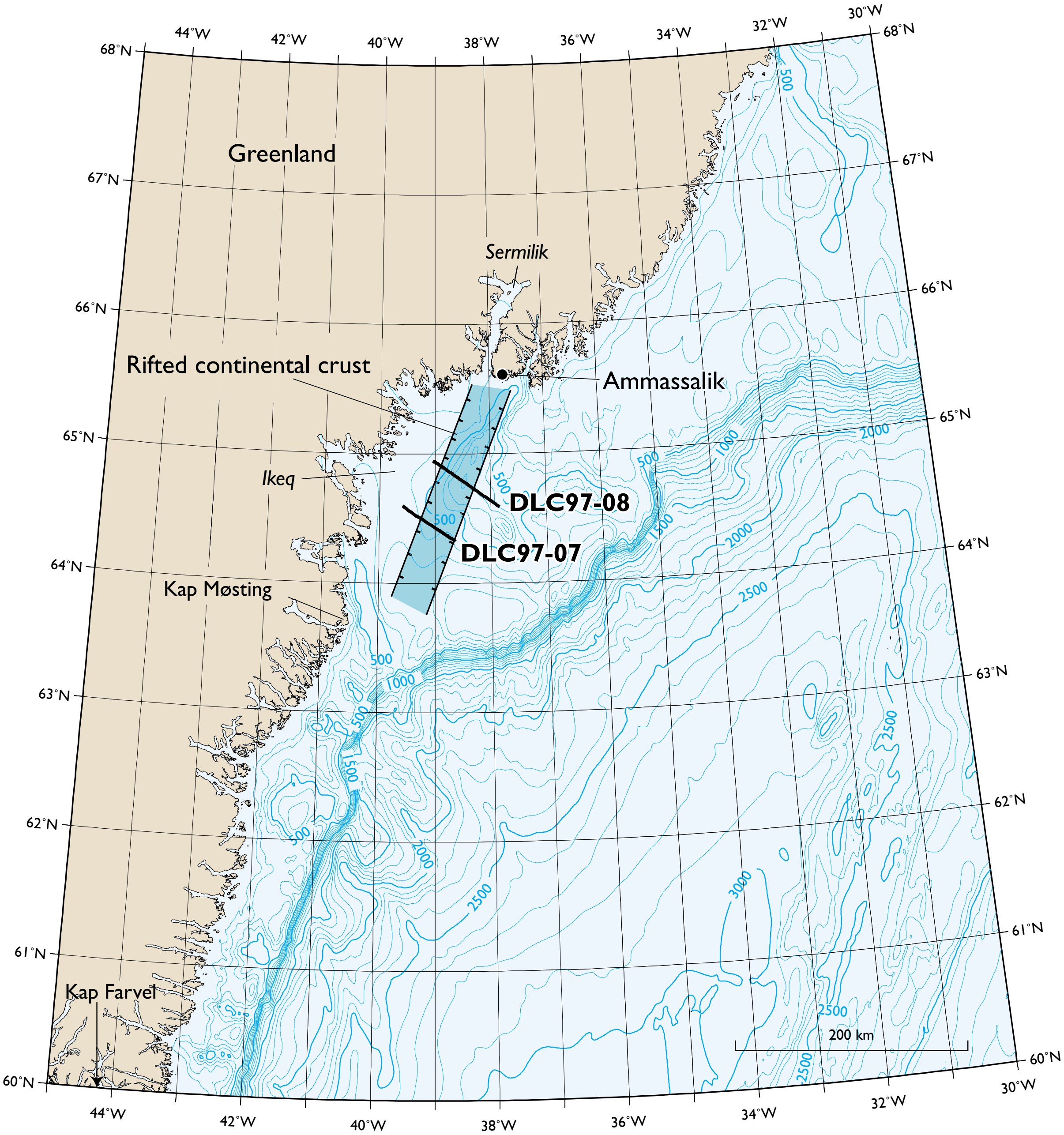

Fig. 4. Location of a hypothesised failed rift arm based on the new data. Seismic line DLC97-08 is shown in Fig. 5.

Region C

A major change in the structure of the East Greenland margin occurs between 64°N and 66°N. The margin shelf is very narrow from Kap Farvel up to Kap Møsting but broadens significantly to the north (Figs 1, 4). In addition, the margin appears to be segmented, with a small offset in the strike of the margin just around Ammassalik. Some of the broadening of the margin is due to erosion and sedimentation patterns in the region. A major segment of the Inland Ice drains towards this area and recent glacial deposits are built up much far-

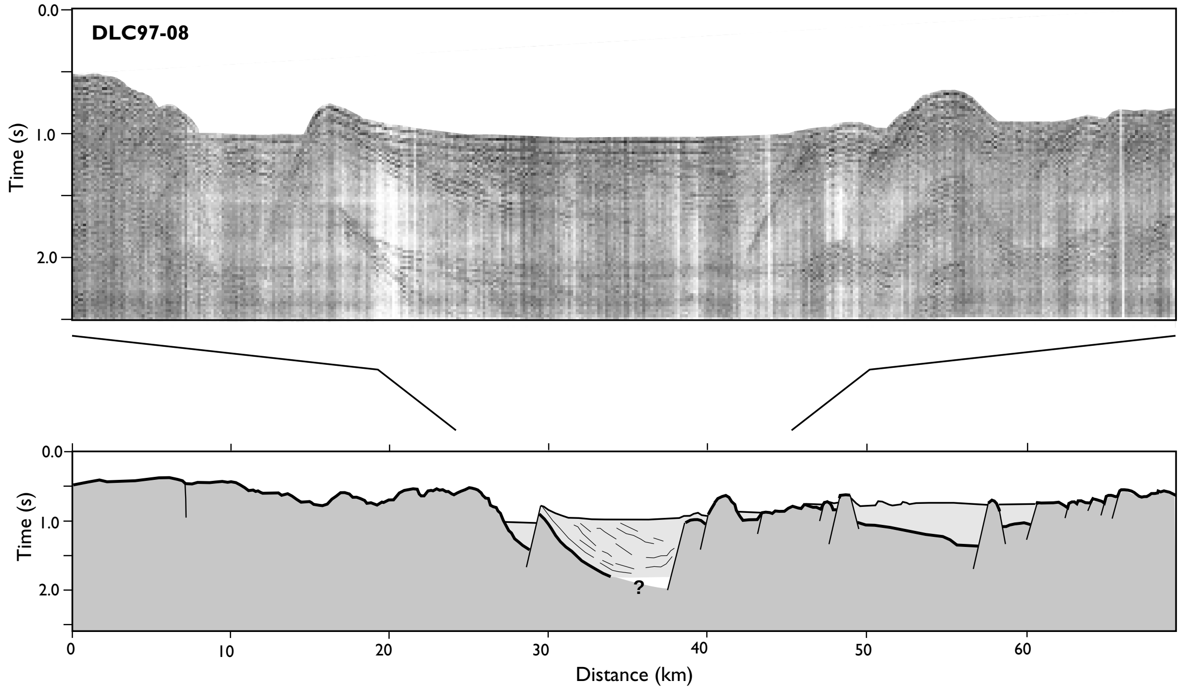

Fig. 5. Line DLC97-08, located south of Ammassalik, see Fig. 4. The possibility that a significant part of the margin in this area is underlain by thinned continental crust must now be considered.

ther out to sea than along other parts of the margin (Larsen 1990; Clausen 1998). However, there may be other factors that contribute to this change. Increased magmatism closer to the inferred plume track could have led to a more prolonged period of excess volcanism that resulted in a broader region of thick igneous crust. Another possibility is that there was a small change in spreading direction and we hypothesised that a failed rift system could extend towards Sermilik. Thus, the margin here may be underlain by rifted continental crust. Two transects (DLC97-07 and 08) were acquired in this region to extend previous seismic lines farther landward and to investigate the possible existence of a failed rift system here. The shipboard stack of DLC97-08 reveals intriguing features that strongly suggest the presence of a substantial rift basin in this region, including an interpreted down-thrown fault block rotated seawards (Fig. 5). The planned 1998 drilling operations will include this structure as a new target, providing information about the age of the basin, the nature of the infilling strata, and the implications of the feature for the tectonic evolution of the margin.

Summary

Overall the cruise was very successful. New high-resolution seismic data were collected in all of the areas we had planned to survey. Although processing of the data is still in progress, the data has already provided us with significant new information that bears on our understanding of the region. Along the EG66 transect, the landward extent of anomalous volcanism appears to be much closer to the coastline than previous interpretations concluded. South of Ammassalik, we discovered evidence for extensional basins of unknown age. Much of this area thus appears to be underlain by rifted continental crust. Further work in this region is now necessary to fully understand the tectonic evolution of the area.

Acknowledgments

Many people contributed to the success of this survey. The professionalism and cooperation of Capt. Larsen and the crew of the R/V *Dana* were a key component to fulfilling the major objectives. Per Trinhammer (AU) and Egon Hansen (GEUS) worked tirelessly operating the seismic gear during the thousands of kilometres of data acquisition. We thank Holger Lykke-Andersen (AU) for his time and efforts and for use of the Aarhus University acquisition system. Jørn Bo Jensen (GEUS) and Stine Rasmussen (AU) are thanked for their contributions at sea and Trine Dahl-Jensen (DLC) for her efforts on shore. EIVA A/S provided significant last minute help setting up the magnetometer and navigation systems. Finally, we thank the Netherlands Institute for Sea Research for providing their airgun-array compressors which worked flawlessly throughout the cruise.

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Mantle xenoliths from Tertiary lavas and dykes on Ubekendt Ejland, West Greenland

Stefan Bernstein and C. Kent Brooks

Mantle xenoliths were found in Tertiary alkaline (basanitic) lavas on Ubekendt Ejland in West Greenland in the mid 1970s by J.G. Larsen. Microprobe analyses of olivine, pyroxene and spinel in two mantle xenoliths, suggested that the xenoliths on Ubekendt Ejland are highly depleted and have high modal olivine contents, and low modal orthopyroxene and clinopyroxene (Larsen 1982). In this respect the mantle xenoliths from Ubekendt Ejland are very similar to the spinel harzburgites from Wiedemann Fjord, in the Tertiary volcanic province of East Greenland (Brooks & Rucklidge 1973; Bernstein *et al.* 1998).

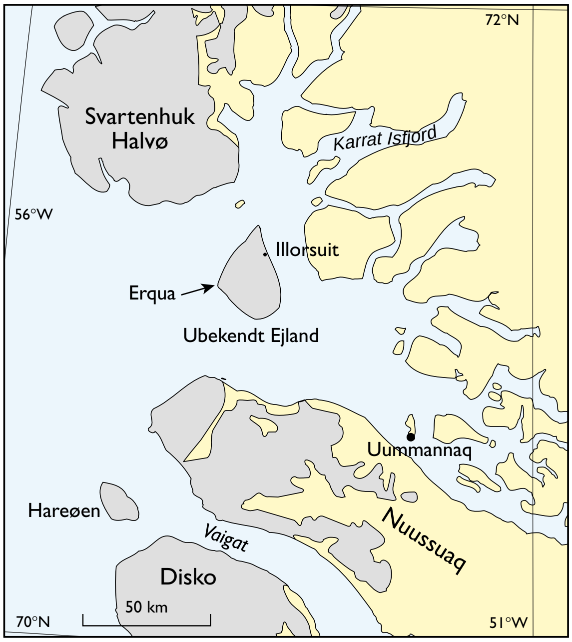

Fig. 1. Basalts (grey) on Ubekendt Ejland are part of the West Greenland Tertiary Igneous Province (e.g. Hald & Pedersen 1975). The pre-Tertiary sediments and Precambrian basement are coloured yellow. Ultramafic xenoliths were sampled from basanitic lava flows and dykes near Erqua on the west coast of Ubekendt Ejland.

Larsen (1981) also reported dykes containing mantle nodules and a varied suite of cumulates and megacrysts, one of which has subsequently been dated to 34.1 ± 0.2 Ma (Storey *et al.* 1998) The basalt flow that carries the xenoliths is from what is defined as the Erqua Formation which occurs at the top of the lava succession in western Ubekendt Ejland (Fig. 1; Drever & Game 1948; Larsen 1977a, b). The basalts have not been dated, but are younger than 52.5 Ma, which is the date obtained for the underlying formation (Storey *et al.* 1998).

During July 1997, we spent three weeks collecting xenoliths and prospecting for xenolith-bearing dykes in the Uummannaq district of central West Greenland. The field work resulted in an extensive collection of xenoliths from an alkaline basalt flow described by Larsen (1977a, b), as well as the discovery of a dyke carrying a large number of ultramafic xenoliths of various origins. The xenolith-bearing basalt flow of the Erqua Formation is exposed in the sea cliffs on the western point of Ubekendt Ejland (Fig. 1). The flow is approximately 10 m thick and xenoliths of gabbro and peridotite occur infrequently, typically spaced several metres apart. Most peridotite xenoliths are angular and between 1 and 4 cm in maximum dimension. Gabbro xenoliths are also angular and are up to 10 cm across. It proved difficult to extract samples from the well-polished surface of the basalt flow, and most had to be drilled and blasted out. A total of 25 peridotite xenoliths were retrieved. They are olivine rich, with > 80% modal olivine, 0–20% orthopyroxene and 1–2% chrome-spinel. Small amounts of clinopyroxene are present in six xenoliths only. Based on texture, mode and olivine composition, the xenoliths can be divided into two groups, a high Mg no. (= atomic Mg/(Mg + Fe) × 100) and a low Mg no. suite. The high Mg no. suite has porphyroblastic texture, with spinel grains in stringers, no

Fig. 2. Block with ultramafic xenoliths in lamprophyre dyke 1.8 km south of Erqua, Ubekendt Ejland. Dunite xenoliths are light brown, while pyroxenite xenoliths are greenish.

clinopyroxene, and highly forsteritic olivine (> 92% Fo). The low Mg no. suite has granular texture, > 2% spinel occurring as disseminated equant grains, clinopyroxene is present, and the olivine has < 91% forsterite.

Ultramafic xenoliths were also found in an approximately 60 cm wide lamprophyre dyke, which is vertical and strikes N–S. The dyke crops out in a stream bed, some 100 m from the shore and about 1.8 km south of Erqua. The basalt that hosts the dyke at this locality is believed to be the next flow overlying the basalt flow with xenoliths described above. About 500 m separates the two xenolith localities. The xenoliths found in the lamprophyre dyke are mainly rounded and from a few centimetres to about 20 cm in maximum dimensions (Fig. 2). Most of the xenoliths are peridotites, i. e. olivine rich with > 90% olivine, 5–10% clinopyroxene and 1–3% chrome-spinel. The peridotite xenoliths have a granular and sometimes cumulate texture, and olivine has forsterite contents in the range 84–88%. Other xenoliths include clinopyroxenites and clinopyroxene-rich peridotites in which the olivines in general have lower forsterite contents (77–84%).

Three other xenolith-bearing localities (two dykes and a small plug), as well as float blocks with ultramafic, mafic and felsic inclusions, together with various megacrysts, were also found but have not yet been subjected to detailed examination.

Preliminary electron microprobe data on olivine compositions are summarised in Figure 3, which shows that there is some overlap between the low Mg no. suite from the basalt flow and the olivine rich (peridotite) xenoliths from the lamprophyre dyke. Olivines from the clinopyroxene-rich xenoliths have lower forsterite contents than olivines from the peridotite xenoliths from both localities. The xenoliths which have olivine with less than 91% forsterite are thought to be cumulates which may have formed in magma chambers during the waning stages of continental rifting in this area. The high Mg no. suite of xenoliths from the basalt flow has olivine

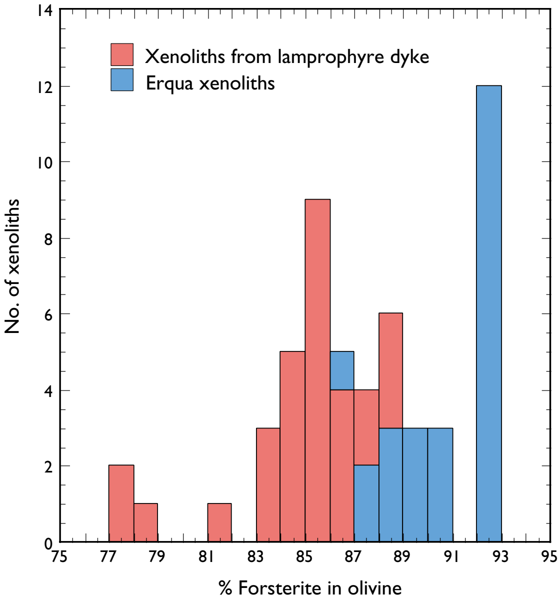

Fig. 3. Forsterite (atomic Mg/(Mg + Fe) × 100) in xenoliths from near Erqua, Ubekendt Ejland (basanite flow) and the nearby lamprophyre dyke. Each sample represents the average of 2–25 microprobe analyses in olivine grains. The variation in forsterite content within single xenolith samples is typically less than 0.5% (relative).

with distinctly higher forsterite contents than other peridotite xenoliths from both localities. Their average olivine has 92.6% forsterite. This is remarkably similar to other refractory spinel peridotites from Kaapvaal, South Africa (Fo = 92.8: Boyd 1989), Udachnaya, Siberia (Fo = 92.8: Boyd *et al.* 1997), Lac de Gras, Canada (Fo = 92.7: Boyd & Canil 1997), and Wiedemann Fjord, East Greenland (Fo = 92.7: Bernstein *et al.* 1998). The depleted harzburgite xenoliths from Wiedemann Fjord, East Greenland can be modelled as the residue after 40% melt extraction at low pressures (20–30 kbar), producing a melt similar to Munro-type komatiites (Bernstein *et al.* 1998). We speculate that the closely similar forsterite content of olivines from these depleted mantle xenoliths reflects extensive melt extraction in the Archaean, with termination of the melting process at the exhaustion of orthopyroxene from the source.

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Late Cenozoic wood from Washington Land, North Greenland

Ole Bennike

The arctic regions are north of the tree line, but nevertheless wood is quite plentiful. Most of this wood in Greenland is driftwood that has floated across the Arctic Ocean, to be eventually deposited on beaches. Following previous deglaciations and isostatic rebound, raised beaches are common, and driftwood may be common below the marine limit. Most driftwood is of postglacial age, but pre-Holocene driftwood has been reported from Greenland and elsewhere in the Arctic.

Some of the pre-Holocene wood derives from trees that grew in the Arctic in the past, when climates were warmer than at the present. Best known are the Late Cretaceous and Early Tertiary diverse floras that comprise many warmth-demanding species including vines, but the wood from these time periods is more or less fossilised. Trees also grew in the Arctic much later, and some of this wood is remarkably well preserved and looks much like postglacial driftwood. Thus when the geologist Lauge Koch observed tree trunks up to 165 m above sea level in the hills of the Kap København area in eastern Peary Land (Fig. 1), he interpreted this as postglacial driftwood (Koch 1926). However, the Kap København Formation is now dated to the Plio-Pleistocene (Bennike 1990). Although no trees have been found in growth position in the Kap København area, it is obvious that the trees grew locally, since leaves, needles, seeds and cones are common, and the rich fossil insect fauna also comprises numerous species that are dependent on trees (Böcher 1995). At two other sites in Peary Land concentrations of pre-Holocene wood are present, namely at Jørgen Brønlund Fjord and at Baggården. The occurrence at Jørgen Brønlund Fjord is situated below the marine limit, and the wood could be driftwood, but the concentration of wood fragments is more indicative of local tree growth (Bennike 1990). At Baggården, wood is found along the shore of the lake and along Sydpaselv that drains into Øvre Midsommersø (Bennike 1990; E. Knuth, National Museum, Copenhagen, archive). A few specimens from this locality archived in the National Museum in Copenhagen (NM VIII A 4512M) are small, abraded and fragmented pieces that do not show the size of the trees.

From Washington Land, pre-Holocene wood has previously been reported from the pre-glacial Bjørnehiet Formation (GGU 211926 and 211929; Jepsen 1982), and from a gravel river bed north of Humboldt Gletscher (GGU 206054). At the latter site many wood pieces were reported at an altitude of 245–260 m above sea

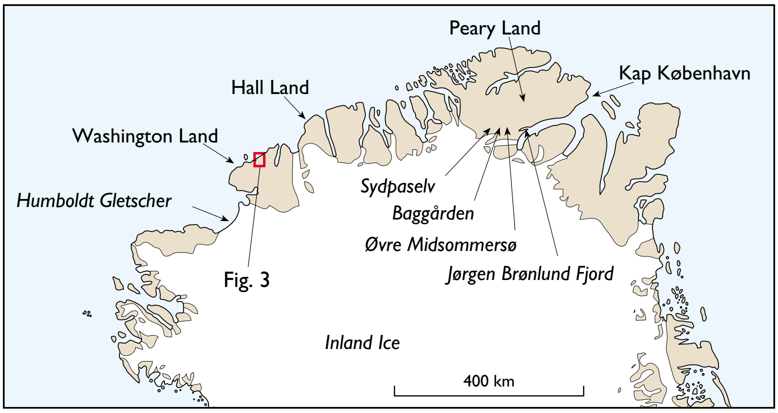

Fig. 1. Map of northern Greenland showing the locations of place names mentioned in the text.

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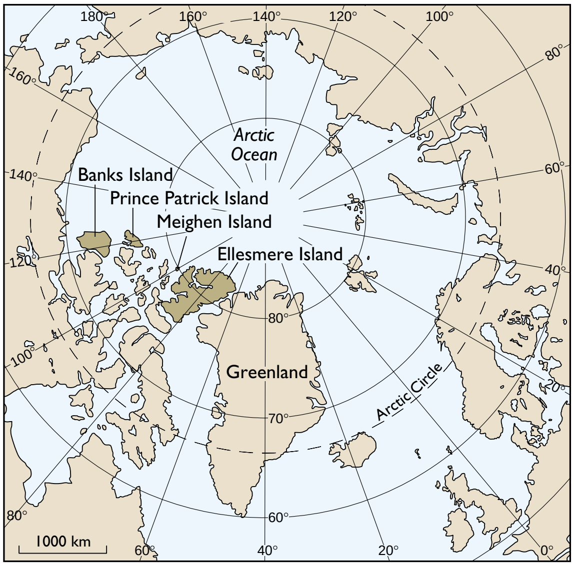

Fig. 2. Circumpolar map showing the locations of place names in northern Canada mentioned in the text.

level (Blake 1987), which is far above the marine limit of the area. Weidick (1978) suggested that the wood is interglacial driftwood that was redeposited by glaciers, but again the concentration of wood fragments is hard to understand, so a source from local tree growth seems more likely.

The wood in North Greenland bears resemblance to wood from the Beaufort Formation and related deposits in northern Canada (e.g., Matthews & Ovenden 1990; Matthews *et al.* 1990; Fyles *et al.* 1994). The Beaufort Formation is assigned to the Miocene and Pliocene. On western Ellesmere Island (Fig. 2), so-called high-level alluvium is fairly widespread. A notable occurrence here, at an elevation of approximately 400 m, is the Mid or Late Pliocene Beaver Pond peat that also contains a rich mammalian fauna, including the extinct rabbit *Hypolagus* that is also present in the Kap København Formation (Matthews & Ovenden 1990; C.R. Harington, personal communication 1994).

During field work in Washington Land in the summer of 1997 a new locality with abundant wood was located along the river that drains into Aleqatsiaq Fjord, at *c.* 80°31.9′N, 65°25′W (Fig. 3), and the purpose of this note is to describe some samples of wood that were brought to Copenhagen. The collection site is *c.* 70 m above sea level. Although no information is available on the height of the marine limit in Washington Land, this is probably below the marine limit, since the marine limit on Hall Land to the east of Washington Land is 100–120 m above sea level (Kelly & Bennike 1992). However, postglacial driftwood is exceedingly rare in Hall Land, and the highest reported comes from an altitude of 56 m (England 1985). Furthermore, the wood from Washington Land does not look like driftwood, since all logs represent very small trees. In spite of a search in the vicinity in 1997, it was not possible to locate the source of the wood (M. Sønderholm, personal communication 1997).

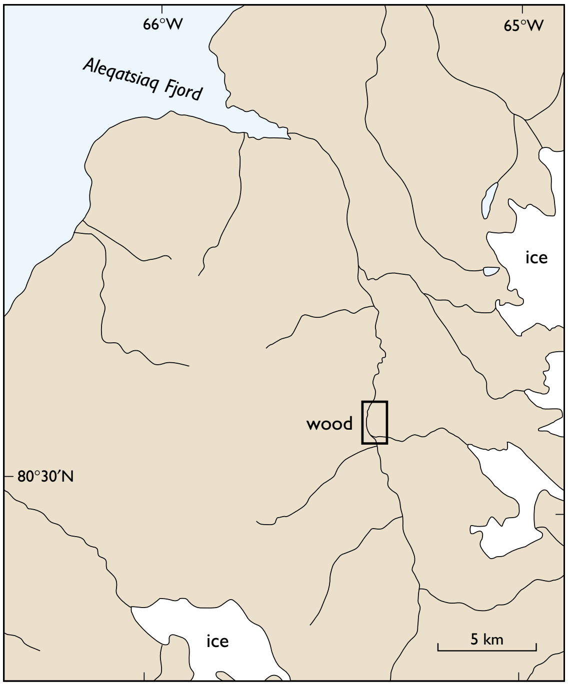

Fig. 3. Map of the Aleqatsiaq Fjord region in Washington Land, showing where the wood pieces described in this report were collected.

Material and methods

A total of 20 samples of wood, mostly trunks of trees but also a few branches and a few small wood fragments, were available for analysis (Fig. 4). Most samples were cut and polished for growth ring analysis using a dissecting microscope. The wood samples were identified by their anatomical structure as studied in tangential, radial and cross sections, using a light microscope. *Larix* and *Picea* wood were distinguished by the features listed by Bennike (1990).

Fig. 4. Some of the wood pieces. From left to right, GGU 442933, 442936, 442935 and 442943.

Results

The specimens are small; the longest piece measured 98 cm in length, and the thickest stem measured 115 mm in diameter (Table 1). The diameter of the longest stems with some roots still attached decreases rapidly from base to top, a conical growth form that characterises tree trunks near the tree line. Stems are distinguished from branches by the morphology of the samples and from the distribution of compression wood. The specimens are strongly abraded, and no bark or branches are preserved. The structure of the wood is well preserved, but the wood is slightly carbonised. Fly holes, presumably from cerabycid beetles, are present in some of the pieces, and borings of bark beetles are also observed.

Table 1. Data on wood pieces from North Greenland

GGU No.	Length (cm)	Diameter* (mm)	Number of rings	Mean ring width† (mm)	Taxon
442933	98	60	150	0.20	*Larix* sp.
442934	92	56	194	0.14	*Larix* sp.
442935	57	36	210	0.09	*Larix* sp.
442936	70	61	*c.* 200	0.15	*Pinus* sp.
442937	64	105	*c.* 320	0.21	*Thuja* sp.
442938	50	115	42	1.10	*Picea* sp.
442939	56	80	40	0.45	*Larix* sp.
442940	34	60	*c.* 100	0.28	?*Larix* sp.
442941	42	48	*c.* 150	0.14	Gymnospermae
442942	50	68	150	0.25	-
442943	34	33	*c.* 240	0.09	*Pinus* sp.
442944	35	-	-	-	?*Larix* sp.
442945	33	59	130	0.23	*Larix* sp.
442946	50	30	220	0.08	*Thuja* sp.
442947	48	55	146	0.17	*Larix* sp.
442948	51	30	?	0.10	*Pinus* sp.
442949	18	32	80	0.18	*Larix* sp.
442950	53	65	152	0.22	*Larix* sp.
442951	33	13	-	-	?
442952	stub	-	-	-	*Pinus* sp.

* Measured midway between root and top where present.
† Often measured along only part of the cross section.

The growth rings are extremely narrow, and many growth rings are only a few cell layers thick. The mean ring width ranges from 0.08 to 1.10 mm (Table 1), which shows that radial growth was extremely slow. It is suggested that the plants were growing at or near the tree line, mostly under pronounced thermal stress during the summer, and probably at the lower limit of tree growth. The widths of the individual growth rings are highly variable, suggesting great variability in summer temperatures during the period of time of the formation of the wood. Another common phenomenon among the samples is the presence of asymmetrical growth rings formed as a result of tilting, indicating growth on unstable soils.

All samples represent conifers; 10 were identified as *Larix* sp., four as *Pinus* sp., two as *Thuja* sp. and one as *Picae* sp. (Table 1).

Comparisons

Information that can provide a basis for comparison with the wood from Washington Land is available from a few sites in North Greenland and northern Canada. Of the tree trunks from the Kap København Formation, only a few measured more than 10 cm in diameter, and the largest sample had a diameter of 18 cm. The two longest trunks were respectively 460 and 335 cm long. The growth rings were extremely narrow, although rather variable; mean ring width was 0.20 to 0.78 mm. Of 119 wood samples identified, 76 were *Larix* sp., 22 *Picea* sp., and a few *Thuja* sp., *Taxus* sp., *Betula* sp. and *Salix* sp. (Bennike 1990). The lack of pines in the Kap København Formation distinguishes that flora from most Late Cenozoic floras from northern Canada.

In Canada, a few of the tree trunks from the Beaufort Formation on Meighen Island (Mid or Late Pliocene) exceed 18 cm in diameter. On Banks Island logs up to 60 cm in diameter are found (Late Miocene and Pliocene), and on Prince Patrick Island some logs exceed 40 cm in diameter (Mid Pliocene). From the Worth Point Formation on Banks Island trunks of *Larix* up to 26 cm in diameter have been reported. *Laric laricina* is the only conifer reported from the Worth Point Formation; this sequence is considered to be around 1.5 Ma old (Matthews & Ovenden 1990).

The floristic composition and the size of the wood fragments from Washington Land bear strongest resemblance to that of the Beaufort Formation on Meighen Island and the high-level alluvium on Ellesmere Island, for which a Mid or Late Pliocene age is suggested, perhaps around 3 Ma.

Acknowledgements

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Pingos at Nioghalvfjerdsfjorden, eastern North Greenland

Ole Bennike

Pingos are isolated, conical mounds up to 50 m high with a core of ice covered by silt, sand or gravel. They are formed in regions where the ground is permanently frozen. Two types of pingo are distinguished, a closed-system and an open-system (Washburn 1979; Pissart 1988). The closed-system type is found on flat plains, whereas open-system pingos are found on valley floors. Open-system pingos grow by artesian pressure (Müller 1959; Washburn 1979). Water from higher altitudes migrates within or below the permanently frozen ground and becomes trapped within the permafrost and freezes to form a lens or core of ice. Active pingos have been reported from Svalbard, Russia, Alaska, Canada and Greenland (Washburn 1979), and fossil pingos from Pleistocene periglacial terrains have been reported from Europe and North America (De Gans 1988).

In Greenland, most pingos have been reported from both East and West Greenland. In East Greenland pingos have been described from the area between 71°30′ and 74°30′N (Fig. 1). In West Greenland most pingos occur between 70° and 72°N. In addition, a pingo and some pingo-like forms have been described from North Greenland (Bennike 1983). All pingos in Greenland are located in valleys, usually on outwash plains.

During field work in 1997 one fairly impressive pingo and several small pingos or pingo-like forms were observed at *c.* 79°30′N in eastern North Greenland. These are the northernmost pingos recorded from eastern Greenland, and the aim of this note is to document and describe these forms. The observations add to our knowledge about the distribution of pingos in Greenland, and a map showing the distribution of pingos in Greenland is presented as Fig. 1.

Setting

Nioghalvfjerdsfjorden is a large fjord *c.* 80 km long and 21 km wide, completely covered by a floating glacier

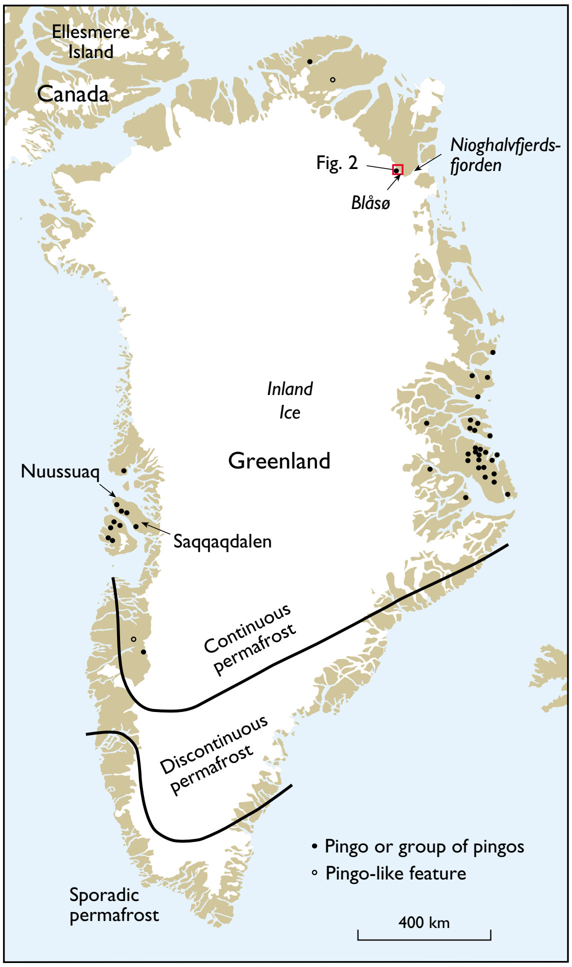

Fig. 1. Map of Greenland showing the geographical distribution of pingos and location of place names mentioned in the text. Compiled from Rosenkrantz *et al.* 1942; Vischer 1943; Flint 1948; Müller 1959; Cruickshank & Colhoun 1965; Lasca 1969; O'Brien 1971; Weidick 1974; Allen *et al.* 1976, Bennike 1983 & unpublished; Funder 1988; Christiansen 1995; Worsley & Gurney 1996; Yoshikawa *et al.* 1996; Scholz & Baumann, 1997. The boundaries between sporadic, discontinuous and continuous permafrost are taken from Weidick (1968).

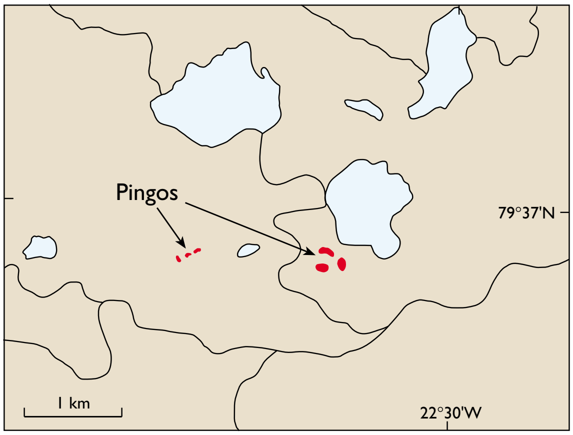

Fig. 2. Sketch map of the outwash plain west of Blåsø near Nioghalvfjerdsfjorden, eastern North Greenland, showing the location of the pingos (shown in red). The elevation of most of the area is below 100 m above sea level. For location see Fig. 1.

tongue. A large lake, Blåsø, is found near the head of the fjord. Nioghalvfjerdsfjorden is very deep and there is undoubtedly no permafrost below it, and this probably also applies to Blåsø. A 3–4 km broad valley is found between the north-western part of Blåsø and the margin of the Greenland ice sheet. The valley is characterised by glaciofluvial outwash plains that consist of thick deposits of sand and gravel. A few large thermokarst lakes are present. The valley bottom is about 50 m above sea level, and the rounded mountains in the area are 400–600 m high.

The high arctic area is semi-arid and desert-like with fell field vegetation. A total of 68 species of vascular plants has been reported from the area (Bay 1992), but most of the plants are confined to small patches with moist soil. The annual precipitation is probably around 150 mm, and the mean temperature for the warmest month 4–5°C. The glaciation limit is *c.* 1000 m above sea level (Weidick 1976); the area was deglaciated about 6000 radiocarbon years BP (O. Bennike and A. Weidick, unpublished data).

Descriptions

Three of the pingos were visited during a short ground stop, whereas the other pingos were only observed at a distance from the ground, or from a helicopter. All pingos are situated on a gravel outwash plain with sand-wedge polygons. For a description of similar sand-wedge polygons from North Greenland, see Bennike (1987). The altitude of the outwash plain is *c.* 30 m above sea level.

The largest pingo (79°36.69′N, 23°03.09′W; Figs 2, 3) is semi-circular in outline, about 100 × 70 m in size and 8 m in height. The slopes have angles of 25–30°, and the top is flat. This is the only feature in the area that can be classified as a well developed pingo. It is partly collapsed, but appears to be still active, with steep slopes and apparently recently uplifted areas with sand-wedges of aeolian sand. Some wind blown sand and silt is found on the lee side (the south side) of the pingo. Here scattered vascular plants are found. The following species were noted: *Dryas integrifolia, Potentilla pulchella, Carex nardina, Poa abbreviata, Papaver radicatum, Salix arctica, Saxifraga oppositifolia, Lesquerella arctica* and *Braya purpurascens.*

About 200 m north and north-east of the pingo two smaller hills are found, with slopes around 20°. In size they measure respectively 30 × 10 m and 20 × 50 m; both are about 5 m high. These hills are more irregular in shape. About 1400 m west of the pingo, several small pingos are found. They are only a few metres high, and measure some tens of metres across. These small pingos could be pingos in their early stages of development.

Discussion

In the earlier literature on pingos in Greenland, the genesis of these conical hills gave rise to much speculation (e.g. Rosenkrantz 1940, 1943, 1950; Rosenkrantz *et al.* 1942; Vischer 1943; Flint 1948). The mounds were often called mud volcanoes, and some authors believed that they were formed by rising methane rich gasses. Müller (1959) made the first thorough study of pingos in East Greenland, and recognised that they were formed by water pressure. The West Greenland pingos are now also recognised as formed primarily by ground water pressure, and an ice core is present in one of the pingos in Saqqaqdalen on southern Nuussuaq (Yoshikawa 1991).

The pingos north of Nioghalvfjerdsfjorden described here are referred to open-system type pingos on account of their location in a major valley. Open-system pingos are found in areas of continuous, but thin permafrost. Therefore pingos are by far most commonly found in the southern part of the zone with continuous permafrost (Fig. 1). The rare occurrences in eastern North Greenland reported here, as well as those in central

Fig. 3. Pingos in the outwash plain at Niohalvfjerdsfjorden, eastern North Greenland. **A**: The largest pingo seen from the helicopter, 100 × 70 m across. **B**: The largest pingo seen from the south (person for scale). **C**: The largest pingo seen from the east. **D**: Pingo north of the largest pingo about 50 m across. **E**: Small pingo west of the largest pingo, with distinct 'crater' and 'crater rim' a few metres high which is associated with the well developed sand wedges. **F**: Small rounded hill, a few metres high, probably a pingo in an early stage of development.

North Greenland (Bennike 1983) and on northern Ellesmere Island (Washburn 1979), are presumably associated with local areas where the permafrost is unusually thin for the latitude.

The pingos in eastern Greenland and North Greenland are small compared to many others pingos that can approach 50 m in height. Nevertheless, they are quite impressive geomorphological features.

Acknowledgements

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Late Quaternary palaeo-oceanography of the Denmark Strait overflow pathway, South-East Greenland margin

Antoon Kuijpers, Jørn Bo Jensen, Simon R. Troelstra and
shipboard scientific party of RV Professor Logachev *and RV* Dana

Direct interaction between the atmosphere and the deep ocean basins takes place today only in the Southern Ocean near the Antarctic continent and in the northern extremity of the North Atlantic Ocean, notably in the Norwegian–Greenland Sea and Labrador Sea. Cooling and evaporation cause surface waters in the latter region to become dense and sink. At depth, further mixing occurs with Arctic water masses from adjacent polar shelves. Export of these water masses from the Norwegian–Greenland Sea (Norwegian Sea Overflow Water) to the North Atlantic basin occurs via two major gateways, the Denmark Strait system and the Faeroe–Shetland Channel and Faeroe Bank Channel system (e.g. Dickson *et al.* 1990; Fig.1). Deep convection in the Labrador Sea produces intermediate waters (Labrador Sea Water), which spreads across the North Atlantic. Deep waters thus formed in the North Atlantic (North Atlantic Deep Water) constitute an essential component of a global 'conveyor' belt extending from the North Atlantic via the Southern and Indian Oceans to the Pacific. Water masses return as a (warm) surface water flow. In the North Atlantic this is the Gulf Stream and the relatively warm and saline North Atlantic Current.

Numerous palaeo-oceanographic studies have indicated that climatic changes in the North Atlantic region are closely related to changes in surface circulation and in the production of North Atlantic Deep Water. Abrupt shut-down of the ocean-overturning and subsequently of the conveyor belt is believed to represent a potential explanation for rapid climate deterioration at high

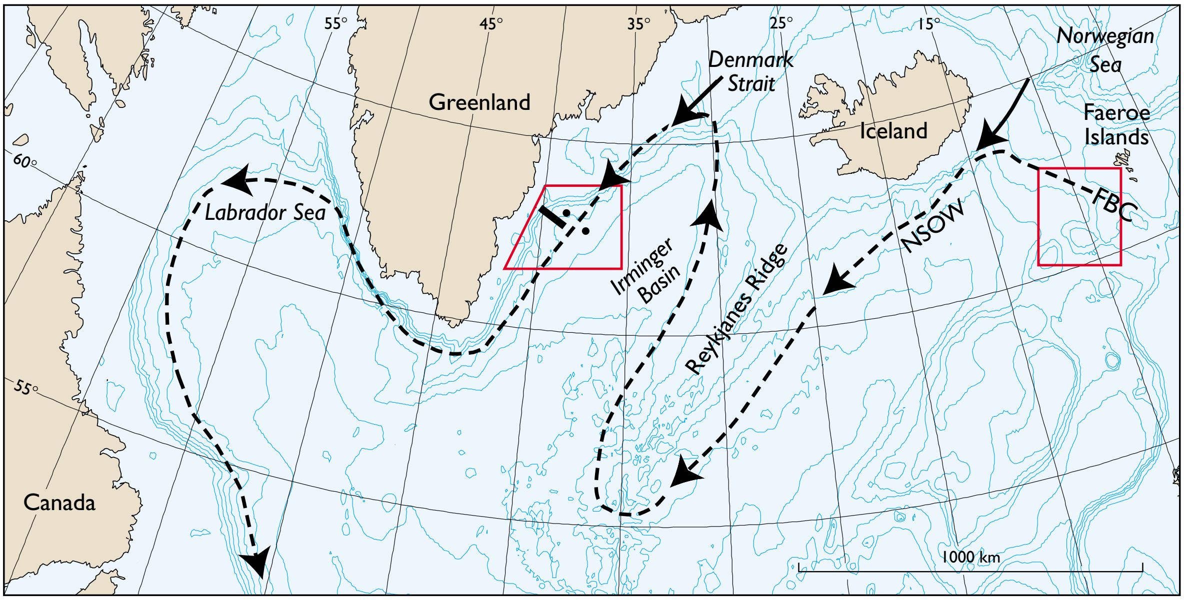

Fig. 1. North Atlantic deep water transport (Dickson *et al.* 1990) and locations of the 'overflow' study area (European North Atlantic Margin project) south-west of the Faeroe Islands, and the present study area off South-East Greenland with the ODP sites 918 and 919 (dots) and the side scan sonar track. A record of the sonar track is shown in Figure 2. NSOW: Norwegian Sea Overflow Water; FBC: Faeroe Bank Channel.

latitudes, such as those that caused the Quaternary ice ages. Here it should be noted, that significant changes in deep convection in Greenland waters have also recently occurred. While in the Greenland Sea deep water formation over the last decade has drastically decreased, a strong increase of deep convection has simultaneously been observed in the Labrador Sea (Sy *et al.* 1997).

Project concept

Within the European North Atlantic Margin project, which is part of the European MAST programme, the former Geological Survey of Denmark (now amalgamated into the Geological Survey of Denmark and Greenland – GEUS) in 1993 initiated palaeo-oceanographic studies of the flow pathway of the Norwegian Sea Overflow Water at the immediate outlet of the Faeroe–Shetland overflow gateway south-west of the Faeroe Islands. Late Quaternary palaeo-oceanographic studies had not previously been carried out in this particular area. Amongst other institutions, Amsterdam Free University has been involved in these studies. Significant changes in overflow intensity have been determined and related to major climate changes, which have occurred during the last 150 000 years (Kuijpers *et al.* 1998). The main aim of these studies has been to investigate the relationship between the fluctuations in the flow of the Norwegian Sea Overflow Water and the late Quaternary climate change. In order to complete the reconstruction of the export of deep waters from the Norwegian–Greenland Sea into the North Atlantic basin, the late Quaternary overflow history of the Denmark Strait pathway must also be taken into consideration.

In the summer of 1995 a project proposal was made together with the Free University in Amsterdam (S.R. Troelstra), which was submitted to the Netherlands Geosciences Foundation. The proposal focused on funding of a research cruise to the South-East Greenland continental margin with the main purpose of collecting piston cores from the sea bed for palaeo-oceanographic research. In addition, some seismic and acoustic work and hydrographic measurements were planned. Site selection for coring would be based mainly on the previously existing high resolution multichannel sleeve gun seismic grid from the nearby Ocean Drilling Program (ODP) drill area (e.g. Larsen *et al.* 1994). The proposal was granted in 1996, and after consideration of various other options, the Russian ice-classified research vessel *Professor Logachev* (St. Petersborg) was selected for the work. Simultaneously an agreement was made with the Danish Lithosphere Centre (DLC) to conduct part of the additional seismic work in collaboration with DLC onboard the Danish RV *Dana* (Hopper *et al.* 1998, this volume).

Work at sea – RV *Professor Logachev*

The research cruise with RV *Professor Logachev* was conducted between 16 August and 15 September 1997, with a port call in Reykjavik on 8 September. Mobilisation of various equipment was made in Aberdeen (14–16 August), while demobilisation was in Kiel (15–16 September). Weather conditions in the research area were favourable throughout the survey period, and during the work in coastal waters there were no major problems with ice. Participants were from various institutions in Canada, Denmark, England, Holland, Russia and Sweden. During the work the vessel proved to be an excellent platform for marine geological work, both for coring and (deep-tow) acoustic work. Most of the work was carried out in the immediate vicinity of the ODP drill sites 918 and 919 and the adjacent area to the south (Troelstra & Kuijpers 1997).

Seismic data acquisition, sub-bottom profiling, and sea floor imaging

Seismic data acquisition was done using a Tisey airgun source, a 350 m long 12-channel hydrophone streamer, and a digital recording system storing data on a (magneto-optical) disk. The signal frequency range was 20–250 Hz. Records from the slope and basin display three seismic sequences that could be tentatively correlated with the regional seismic stratigraphy proposed by Clausen (1997). While the seismic facies of the upper two sequences clearly indicate a dominance of downslope sedimentary processes and enhanced contour current activity, the seismic facies of the lowermost sequence indicates a relatively low-energy depositional environment. The lower unconformity marking this change is probably of (Mid) Miocene age. An example of a normal fault was observed, cutting the basaltic basement.

Sea bed characteristics and shallow sub-bottom structures were recorded, using a digital hull-mounted (25 transducers) sediment echosounder system (2–15 kHz). The sediment echosounder records showed strong reflectivity, and relatively little penetration in most parts of the study area.

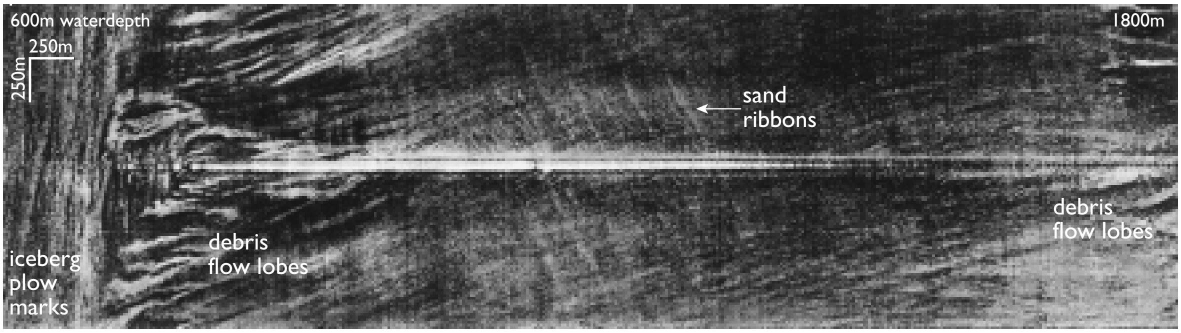

Fig. 2. Sonograph from the South-East Greenland margin, showing iceberg plow marks on the outer shelf (water depth 600 m), and mass and debris flow structures on the upper part and at the base of the continental slope, where water depth is 1700–1800 m. Longitudinal bed forms (narrow sand ribbons and streamers) of 'infinite' length indicate the high-velocity core of south-flowing Labrador Sea Water between 900 m and 1500 m water depth

Acoustically stratified sediments are mainly confined to the northern part of the surveyed continental rise and adjacent basin, where sub-bottom penetration generally was in the range of 10 to 25 ms.

Deep-tow side scan sonar profiling was carried out along six transects with an orientation approximately perpendicular to the continental slope, covering water depths ranging from about 500 m to more than 2000 m. For this purpose an Oretech 30 kHz dual channel (2 × 1000 m range) side scan sonar device with a 3–7 kHz sub-bottom profiler and underwater navigation facilities was deployed. The digital data acquisition unit and acoustic data processing software was developed by Polarexpedition, St. Petersborg, Russia. The side scan profiles provide highly informative records of the South-East Greenland continental margin setting, showing large current-parallel iceberg plow marks on the outer shelf, whereas on the slope, mass flow and debris flow features occur, locally cut off by (Holocene) sand streamers and narrow sand ribbons of 'infinite' (> 2000 m) length (Fig. 2). The distribution of these bed forms demonstrates that the strongest (southerly) bottom currents are confined to water depths between 900 and 1500 m, which corresponds to the Labrador Sea Water depth stratum shown by hydrographic measurements (Dickson & Brown 1994). The bed form type dealt with indicates the (episodic) occurrence of very strong currents (at least 0.8–0.9 m/s). This current speed is 2–3 times higher than found so far by hydrographers. Both mass flow deposits, erosional features and current-induced bed forms are also seen on the continental rise. The sub-bottom profiler and side scan sonar records from the central and northern basinal part of the study area reveal more regular sub-bottom reflectors and a smoother relief incised by a few turbidite channels, as already reported by Johnson *et al.* (1975).

Sediment coring

After initial site selection based on sleeve gun seismic information, final positioning when deploying the coring equipment was carried out with the help of information from the digital hull-mounted sediment echosounder system. This enabled release of the corer at the most favourable position, in particular in areas where strong variation of (sub)bottom characteristics occurred over short (50–150 m) distances, i.e. within the range of GPS navigational accuracy.

A total of nine box cores, eight piston cores and one gravity core were collected. The piston cores obtained in the area have a length of 7–9 m, while on transit from Aberdeen to Greenland a 10 m core was retrieved from a small basin on the eastern flank of the Reykjanes Ridge, south of Iceland. In addition, a giant video-grab was deployed off the Greenland margin, which showed a sea floor covered by large dropstones. The grab sample, 1–2 tons of sediment, contained a large variety of basaltic, granitic and sedimentary rocks, which will provide information on both the origin of the icebergs and the glacial fan sediments in the area.

Almost all sediment cores were logged onboard for their magnetic susceptibility signal, opened and described. Smear-slides were taken and analysed by microscope for lithogenic and biogenic components (diatoms, foraminifera, calcareous nannoplankton, dinoflagellates). The deep water (> 1800 m) cores consist mainly of (late) glacial turbidite sequences underlying a coarsening-upward Holocene top unit indicative

Fig. 3. View of RV *Professor Logachev* at rendezvous with RV *Dana* for transferring seismic information, 1 September 1997.

of increasing deep water circulation. Two cores taken from the outer shelf below the Polar Front Zone where cold surface waters of the south-flowing, ice-laden, East Greenland Current meet the relatively warm surface waters from the Irminger Basin, are of particular interest. Holocene fluctuations of this zone may thus be reconstructed, whereas basal glaciomarine sediments and a 4 m thick varved sediment unit are likely to provide information on the deglaciation history of the South-East Greenland margin.

Hydrographic measurements

Hydrographic measurements and sampling included temperature measurements, plankton net and water sampling for determination of the planktonic foraminiferal fauna and associated DNA research, analysis of stable isotopes (O/C), determination of the calcareous nannoplankton assemblages, and the collection of water samples for determination of the regional C-14 reservoir age. The location of the Polar Front Zone was accurately determined with the aid of temperature measurements, and water samples were collected accordingly.

Work at sea on RV *Dana*

After mobilisation, 17–20 August 1997, the RV *Dana* left Hirtshals, Denmark, on 20 August 1997, and arrived in the survey area off South-East Greenland on 27 August. The seismic lines planned to be recorded within the framework of the VU–GEUS palaeo-oceanographic project were run under favourable weather conditions in the period 27–31 August. Positioning of these lines was made over a large fan-like bathymetric structure extending into the basin near 62°N immediately south of the pre-existing ODP seismic grid. The following main part of the DLC survey was concentrated in areas further to the north, and after successful completion Reykjavik was reached on 23 September; the vessel then returned to Hirtshals (see cruise report RV *Dana;* DLC 1997).

The seismic system used included a cluster of four 40″ TI SG-I sleeve guns and a 96 channel, 594 m long hydrophone streamer. Storage of the digital data was on 3490E tapes. Real-time processing and display of the data is an essential component of the system. For high resolution seismic information, in particular on the uppermost sedimentary sequences, an Elics recording system was also used.

Prints of the seismic records collected during the VU–GEUS leg of the survey were transferred from RV *Dana* to RV *Professor Logachev* on 1 September using a line-firing rocket followed by ship-to-ship container transport (Fig. 3). The data exchange also included other material of crucial interest. This seismic information formed the basis for the selection of additional coring sites for RV *Prof. Logachev* in the southernmost part of the target area not covered by the pre-existing ODP seismic grid.

The large fan-like structure at 62°N, referred to above, to a large extent was found to comprise mass and debris flow deposits with a considerable amount of coarse sediment. This is clearly indicated by the strong reflectivity on sonographs and a lack of acoustic penetration on the sub-bottom profiler records. A suitable site for piston coring was found only in the distal part of the fan. One further site was selected in a local basin on the outer shelf. In addition, a box core was taken from the level of Labrador Sea Water flow at intermediate depth on the continental slope; this showed a late glacial to Holocene (hemipelagic) sediment unit with a characteristic coarsening upward trend. This trend was found also in cores from the central and northern part of the target area. Further palaeo-oceanographic investigations of various biogenic components and associated stable isotopes together with acceleration mass spectrometry C-14 dating are expected to reveal more details of the circulation regime and timing of the major oceanographic events which occurred in this area during the late Quaternary climate change.

Acknowledgements

We gratefully acknowledge the Netherlands Geoscience Foundation for financing of the field work with additional support provided by GEUS. Master and crew of RV *Professor Logachev* and RV *Dana* are thanked for excellent cooperation. In addition, successful coring would not have been possible without the skilful technical assistance of Jack Schilling and Leon Wuis (Netherlands Institute for Sea Research). Cooperation with the Danish Lithosphere Centre, and during the work at sea in particular with John R. Hopper, Chief Scientist on board RV *Dana*, is highly appreciated.

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Labrador Sea circulation and climate variability over decade to millennial time scales

Jonathan T. Overpeck, Ole Bennike and Alex Robertson

The Labrador Sea is one of the primary areas of deep water formation in the North Atlantic Ocean, and is therefore a key region for regional- and global-scale ocean thermohaline circulation and climate variability studies (e.g. Sy *et al.* 1997). Since high resolution records are difficult to obtain due to low sedimentation rates and bioturbation in the Labrador Sea itself high resolution proxy records must come from regions surrounding the Labrador Sea. Here we report on reconnaissance work carried out on coastal lakes in Greenland. The primary objective of this study is to generate annually-dated lake sediment records of climate variability for the last 2000 years. A second objective is to generate century-resolved, quantified, radiocarbon dated records that extend back to the last deglaciation. Finally, we will also attempt to retrieve lake sediments from ice-free time periods of the last glacial stage or the last interglacial stage; such pre-Holocene lake sediments have already been successfully recovered from lakes on Baffin Island, in Canada (Wolfe & Härtling 1996; Miller *et al.* in press). This work will improve the understanding of how the Labrador Sea modulates ocean circulation as well as North Atlantic, Arctic, and global climate.

Reconnaissance field work was carried out in West Greenland in the summer of 1996 (Anderson & Bennike 1997); in the summer of 1997 further reconnaissance studies were undertaken in the area between Kap Farvel and Søndre Strømfjord (Fig. 1). The objectives of these studies were to locate basins with annually laminated (varved) sediments, as such sediments allow a dating uncertainty of only a few years (Hughen *et al.* 1996). We concentrated our initial efforts on low-elevation isolated basins which can contain salt water below a freshwater cap as a result of recent isostatic uplift or tidal interaction with the modern ocean. These basins can become density stratified and meromictic, resulting in anoxic bottom water and the preservation of laminated sediment (Fig. 2). Similar basins are well known from arctic Canada where they have provided high resolution proxy climate records for periods of up to 500 years (Hughen *et al.* 1996). The lake Sælsøen in North-East Greenland, at latitude 77°N, is the only such isolated basin previously identified in Greenland (Trolle 1913). In addition to the work in Greenland, similar work

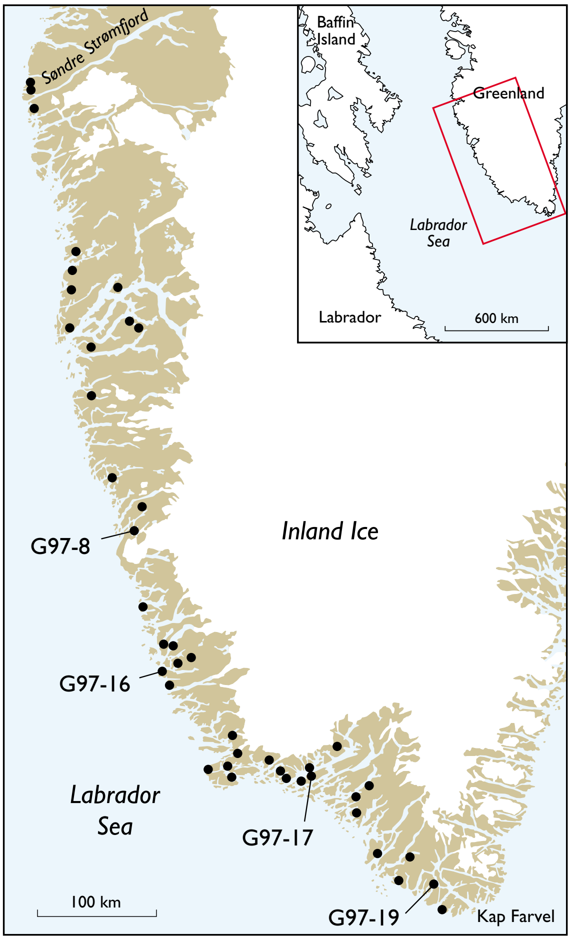


Fig. 1. Map of south-western Greenland showing the locations of the basins sampled during the 1996 and 1997 field seasons.

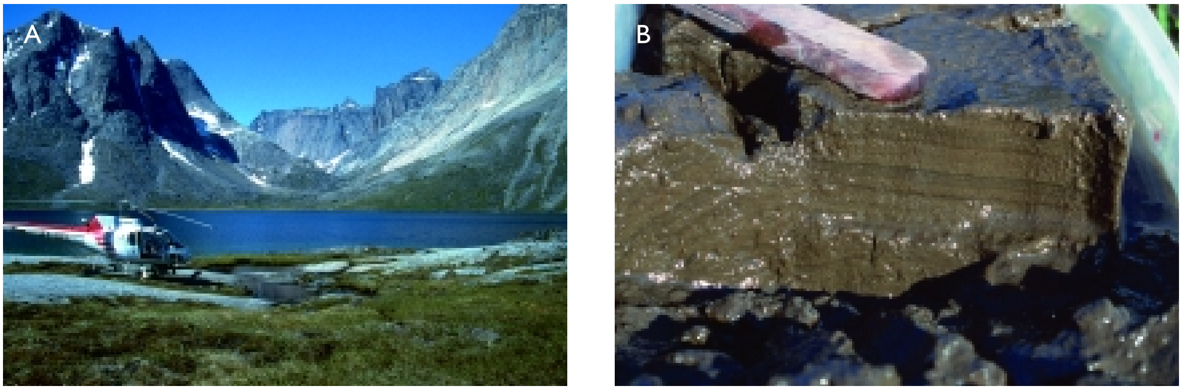


Fig. 2. **A**: Lake G97-19 (60°04.9′N, 44°16.0′W) in the Kap Farvel area, South Greenland. The lake measures about 800 × 1000 m, and the cliff faces next to it are more than 1000 m high. **B**: Laminated sediments collected at a water depth of *c.* 50 m in lake G97-17 (60°51.2´N, 46°28.1´W). For locations see Fig. 1.

is also in progress on coastal Labrador, on the southwestern side of the Labrador Sea.

Methods

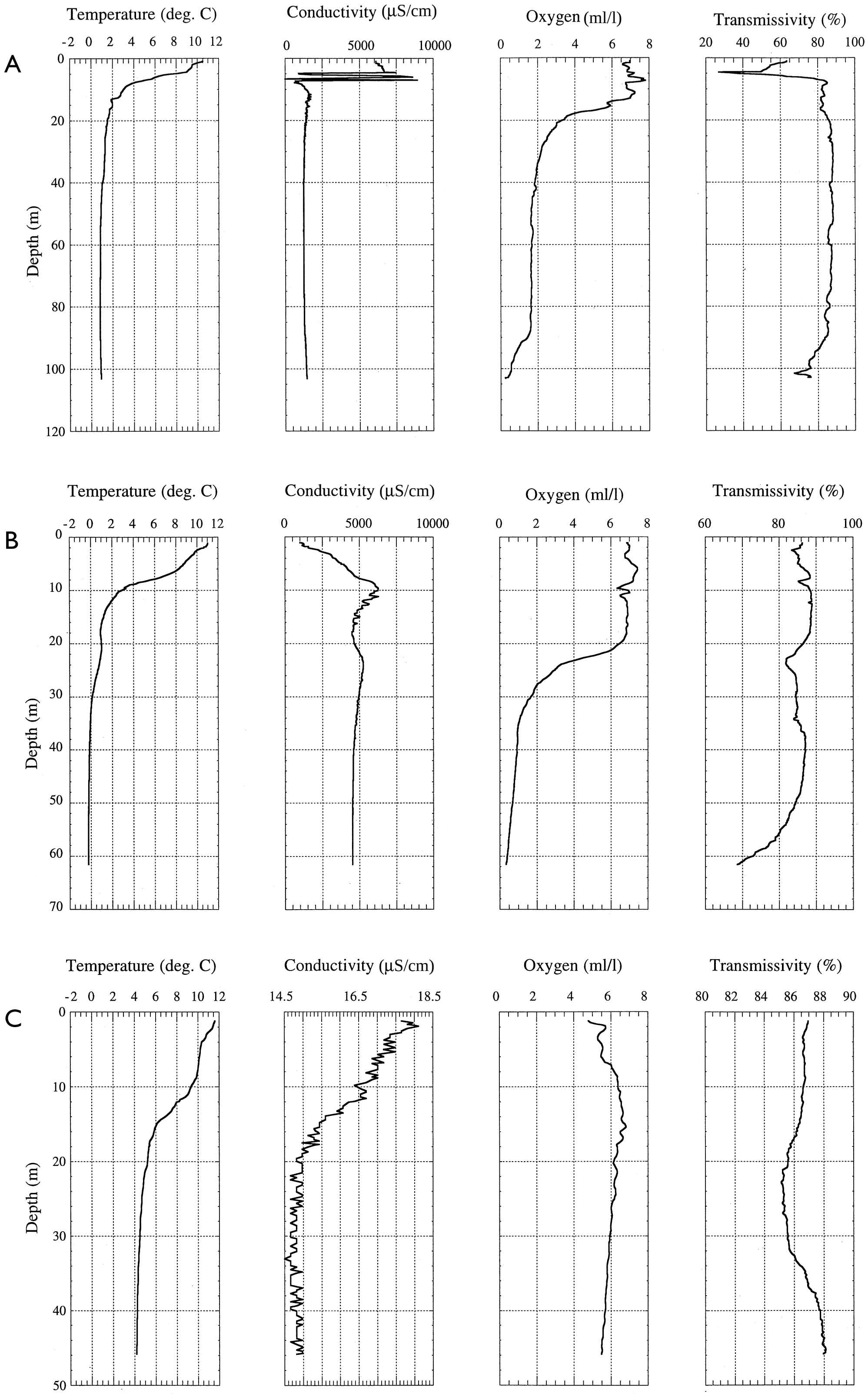
Helicopters from Greenlandair Charter were used for transport to 14 lakes in 1996 and 31 lakes in 1997 (Fig. 1); an inflatable boat was used on the lakes. We collected small surface sediment samples (0–2 cm) with an Ekman dredge and checked the sediment for laminations. Larger sediment samples for macrofossil and submerged bryophyte samples were collected from some of the basins. Surface water samples were collected for stable isotope and water chemistry analyses; moss polsters were collected for pollen analysis. The vegetation around the lakes was also briefly described. Data provided from these samples will mainly be used for calibration studies. In 1997 we measured temperature, conductivity, dissolved oxygen content, light transmission, density, and pH of the water column, using a Seabird CTD profiler.

Results

During the two summers 43 basins in Greenland were visited, and the eastern North America network of sediment-climate proxy calibration sites was expanded into low arctic and subarctic regions. Some of the basins were marine throughout, a few appeared to be meromictic, while the majority were fresh water basins (Fig. 3). Surface area varied from less than 10 to *c.* 1500 ha but most basins had areas around 50 ha. The deepest basin sampled was slightly more than 100 m deep, but 20–50 m was a more normal water depth. The most promising sites that are likely to contain varved sediments were fresh, dilute lakes that are deep in relation to surface area, and surrounded by sheltering mountains. Apparently the shelter in combination with the long period of ice cover, hinders mixing of the water masses so that bottom waters become anoxic. No basins were found containing isolated salt water at depth.

Macrofossil analyses

Sediment samples from 22 lakes were analysed for macroscopic plant and animal remains. Sample size varied from 100 cm^3 to 3400 cm^3, and the samples were collected from *c.* 2 cm to *c.* 20 cm below the sediment surface. Remnants of land plants were found to be fairly frequent even though many of the samples were collected in rather deep water, quite far from the shore. Thus it should be possible to extract enough material from cores of terrestrial plants for accelerator mass spectrometry (AMS) radiocarbon dating. Most common were leaves and fruit stones of *Empetrum nigrum*, leaves of *Vaccinium uliginosum* and nutlets, female catkin scales and leaves of *Betula* sect. *Nanae*. Remains of *Juniperus communis* and *Betula pubescens* were found in sediments from a few of the most southerly lakes. *Salix herbacea* leaves were found to be quite common, although this tiny willow was only noted at a few of the lakes. In contrast to land plants, remains of macrolimnophytes were only found in a few lakes; and were only represented by the bryophyte *Drepanocladus (=Warnstorfia) exannulatus*. Marine basins with black,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B
Temperature (deg. C)
-2 0 2 4 6 8 10 12
Conductivity (µS/cm)
0 5000 10000
Oxygen (ml/l)
0 2 4 6 8
Transmissivity (%)
60 80 100
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0 10 20 30 40 50 60 70
C
Temperature (deg. C)
-2 0 2 4 6 8 10 12
Conductivity (µS/cm)
14.5 16.5 18.5
Oxygen (ml/l)
0 2 4 6 8
Transmissivity (%)
80 82 84 86 88 90
Depth (m)
0 10 20 30 40 50

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Fig. 3. Limnological measurements from basin G97-8, G97-16 and G97-17. For locations see Fig. 1. **A**: G97-8 (62°43.8′N, 49°59.7′W) shows an anomalous situation with fresh water overlain by *c*. 5 m of denser salt water. The top-sediments are glacial clay/silt. **B**: G97-16 (61°33.8′N, 49°06.5′W) is a salt water basin with brackish and fresh water in the upper 10 m. The top-sediments are marine, homogeneous gyttja, even though the bottom waters are almost anoxic. **C**: G97-17 (60°51.2′N, 46°28.1′W) is a fresh water basin. The top-sediments are laminated algal gyttja, in spite of the apparent presence of oxygen in the waters near the bottom.

sulphide-rich but bioturbated, non-laminated sediments contained the highest concentration of macroscopic remains of land plants. Iron-stained sediment which was found in some lakes contained few, poorly preserved macrofossils. It was also evident that it was easy to distinguish between marine-brackish and freshwater sediments on the basis of macrofossil analysis.

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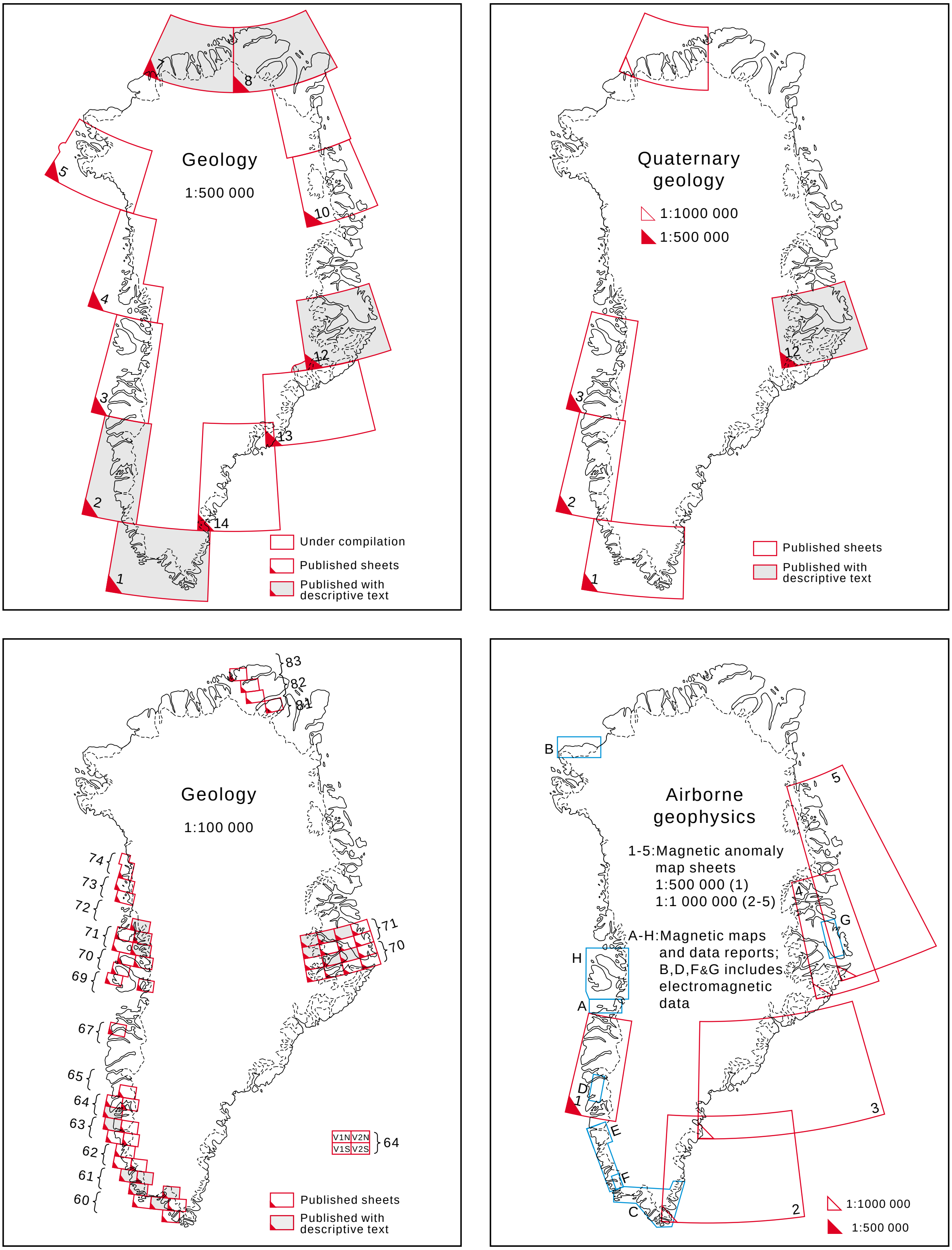

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