GEOLOGY OF GREENLAND SURVEY BULLETIN 191 • 2002

Review of Greenland activities 2001

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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Edited by
A.K. Higgins, Karsten Secher and Martin Sønderholm

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Keywords
Geological mapping, Greenland activities 2001, limnology, marine geophysics, mineral resources, palynology, petroleum geology, sedimentology, sequence stratigraphy, stratigraphy.

Cover
A major landslide was reported from the southern shore of the Nuussuaq peninsula in November 2000 (see Pedersen *et al*., page 73). During the follow-up field studies, periodic minor rock falls created dust clouds that prompted the local population to designate the area as the 'smoking mountains'. Highest summits are 1900 m above the fjord. View to the east from a vantage point on the island of Disko. Photo: Stig A. Schack Pedersen.

Frontispiece: facing page
Outcrop of the contact zone of a 20 m wide kimberlitic dyke south-west of Kangerlussuaq airport, southern West Greenland. This dyke is one of the largest known kimberlite dykes in the world. The locality is marked J on Fig. 2 in Jensen *et al*. (page 58).
Photo: Sven Monrad Jensen.

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Geological Survey of Denmark and Greenland
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Phone: +45 38 14 20 00, fax: +45 38 14 20 50, e-mail: geus@geus.dk
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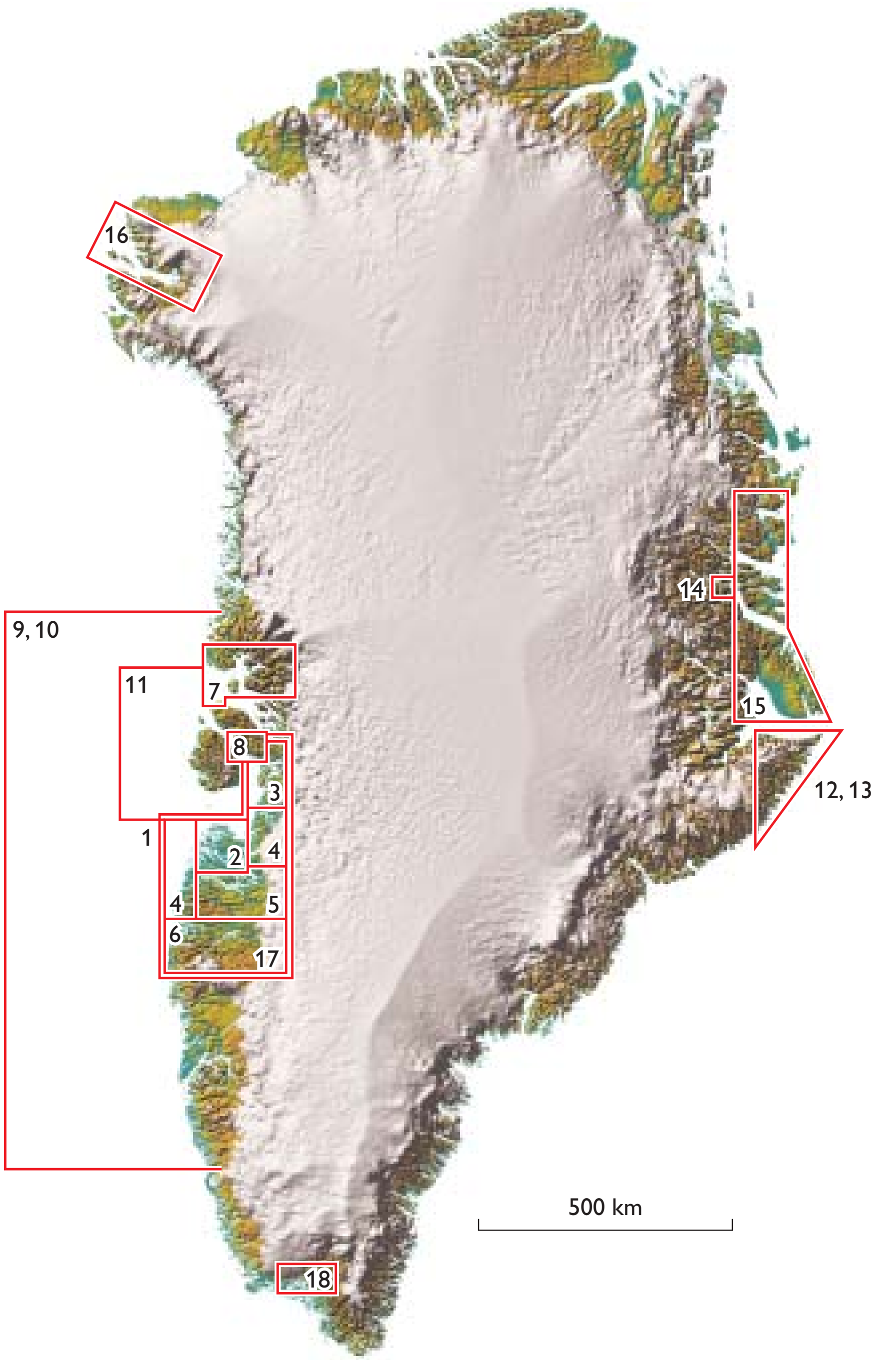


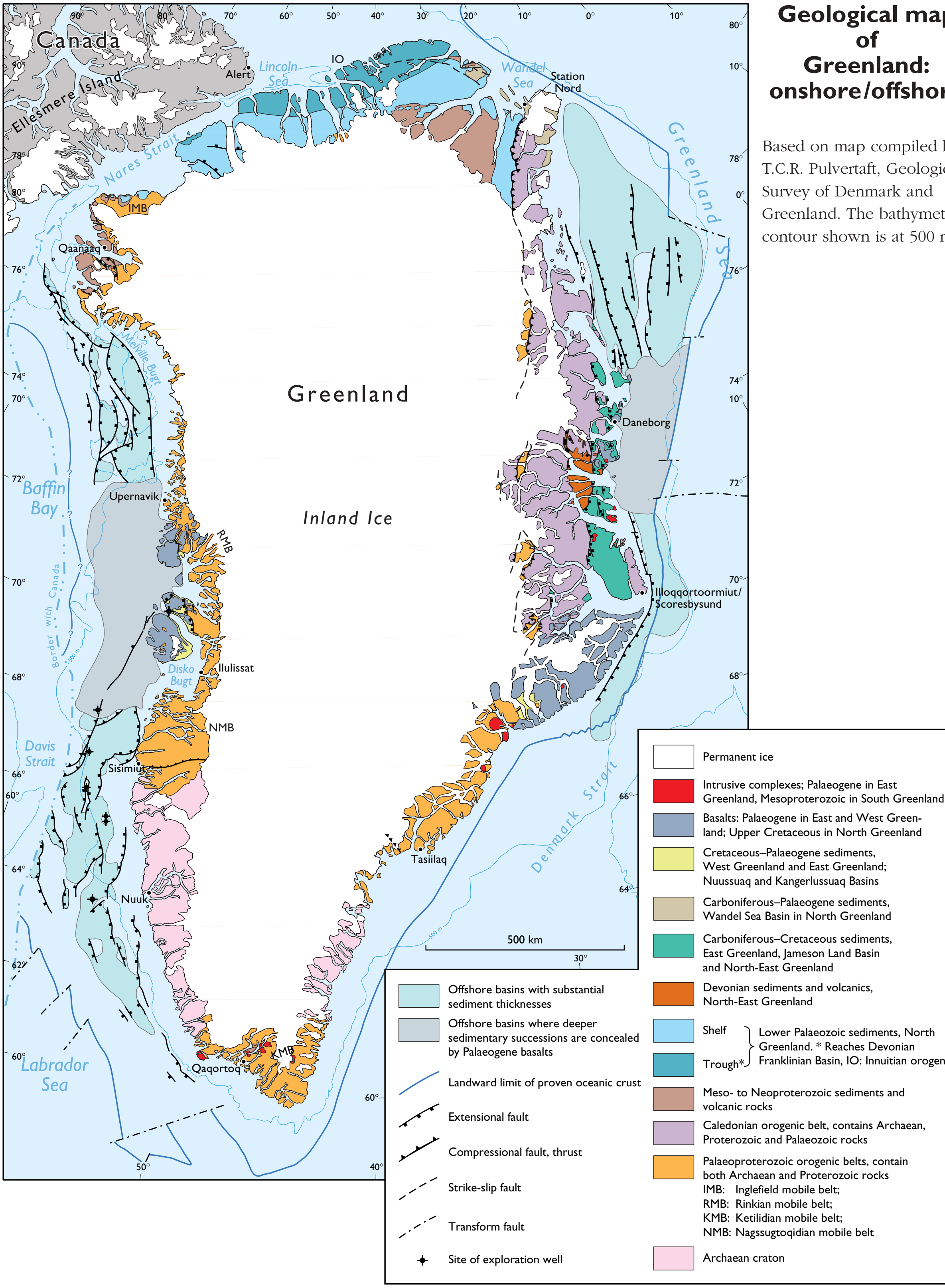
Physiographic map of Greenland showing the locations discussed in the 18 technical papers of this volume. The map is reproduced with courtesy of the National Survey and Cadastre, Copenhagen. For a full list of Survey field activities in 2001 and for the geographical subdivisions as used in this bulletin, see the map in the directorial review (Fig. 1, page 10).

Contents

Numbers of articles correspond to those on the map opposite

Geological map of Greenland: onshore/offshore

Based on map compiled by T.C.R. Pulvertaft, Geological Survey of Denmark and Greenland. The bathymetric contour shown is at 500 m.



The year in focus, 2001

Kai Sørensen
Director

Field activities in Greenland by the Geological Survey of Denmark and Greenland (GEUS) in 2001 were again many and varied. They included economic investigations of crystalline basement and sedimentary rocks in North-West Greenland, and a systematic mapping project combined with resource evaluation in the boundary zone of the Nagssugtoqidian and Rinkian mobile belts of central and southern West Greenland. In addition, studies of the Vendian to Lower Palaeozoic successions in North-East Greenland and of the Palaeogene sediments of central East Greenland were carried out, a major aeromagnetic survey was flown in central West Greenland, and investigations of Holocene lake sediments in southern West Greenland were continued.

In 2001 the proportion of GEUS human resources committed to Greenland activities compared favourably with that in preceding years, although financial resources allocated to Greenland have experienced a marked downward trend over recent years (Table 1). The latter reflects primarily the decrease in Greenland field activities of the Danish Lithosphere Centre (DLC), which is administratively attached to GEUS, as well as a reduction in funding from external sources. Despite their much reduced field activities in Greenland, a significant proportion of DLC's research in 2001 was still related to Greenland. An additional factor influencing the figures for expenditure quoted in Table 1 is of a technical nature in the sense that although aeromagnetic surveys were flown in both 1999 and 2001, the contractual expenses of acquisition were included in the figures for external funding in 1999, but not in the figures for 2001.

The primary source of the Survey's funding is the Finance Law appropriation from the Danish State. The proportion of this grant allocated to Greenland-related activities is based on annual work programmes planned in consultation with the Greenland authorities, in particular the Bureau of Minerals and Petroleum (BMP) of the Government of Greenland. The planned activities are approved by the Board of GEUS, on which BMP is represented.

External sources of funding for Greenland activities in 2001, as in previous years, came primarily from BMP and from Danish and international research foundations of which the most important are the Danish Natural Science Research Council, the Carlsberg Foundation, the Commission for Scientific Research in Greenland and the European Union. DLC is funded by the Danish National Research Foundation.

Regional geology and mapping

Systematic mapping was undertaken in 2001 in the Aasiaat region of central West Greenland, located at the transition between the Rinkian and Nagssugtoqidian

Table 1. Key statistics on Survey resources

RESOURCES	2001	2000	1999
HUMAN RESOURCES			
Permanent staff (man-years)			
GEUS personnel*	346	354	356
Allocated to Greenland work	80	93	87
Greenland field work (persons)			
Total number of participants†	77	92	85
DLC persons involved	3	21	27
FINANCIAL RESOURCES (million DKK)			
GEUS Finance Law appropriation	140	138	135
Of this spent on Greenland activities	32	32	33
GEUS external funding‡	63	77	78
Of this spent on Greenland activities	17	22	28
DLC spending on Greenland activities	8	14	18
Total expenditure on Greenland activities	57	68	79

* excludes DLC staff of *c.* 20.
† includes DLC and external scientists.
‡ excludes DLC funds.
From Annual Accounts 2000/2001 and internal/external sources.

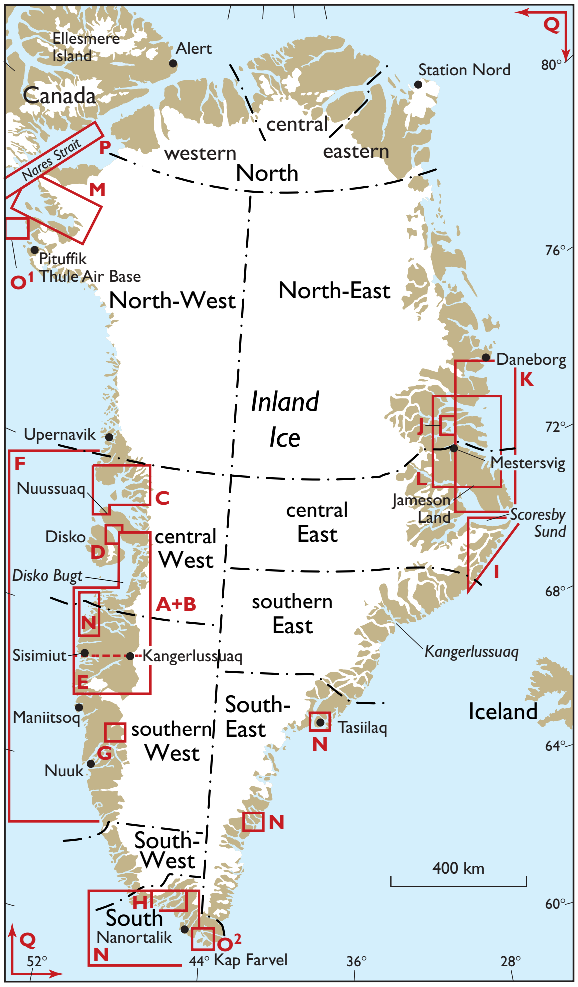


Fig. 1. Map showing the regions in which Survey field activities were carried out in 2001: frames **A–Q**. **Letters** in bold in the list below indicate those regions for which articles are presented in this volume; **numbers** 1–18 in parentheses refer to the articles as listed in the Contents and on the adjoining index map (pages 4 and 5).

A: West Greenland; regional mapping (1, 2, 3)
B: West Greenland; mineral resource assessment (4, 5, 6)
C: Svartenhuk Halvø region; airborne geophysics (7)
D: Nuussuaq region; general geology, landslide investigations (8)
E: Kangerlussuaq area, southern West Greenland; investigations of lake sediments (17)
F: West Greenland; petroleum geology and seismic interpretation (10, 11, 12)
G: Isukasia region; *Isua Multidisciplinary Research Project*, regional geology and geochronology
H: Narsaq region; glaciology (18)
I: Scoresby Sund region; stratigraphy (12, 13)
J: North-East Greenland; stratigraphy and palaeontology (14)
K: North-East Greenland; geochemistry (15)
L: North-East Greenland; *MINEO* and *HyperGreen* projects, hyperspectral ground control
M: *Qaanaaq 2001*; mineral resource assessment, geochemistry and regional geology (16)
N: South, South-East and central West Greenland; ornamental stone investigations
O[1] and O[2]: North-West and South Greenland, respectively; environmental history research
P: North-West Greenland; geophysical research
Q: Throughout Greenland; *GLATIS* and *NEAT* projects, geophysical research

Proterozoic mobile belts (Fig. 1, **A**). This project is aimed at the production of two 1:100 000 geological map sheets, and is an extension of the field work in 2000 on the Ussuit map sheet of the Nordre Strømfjord area immediately to the south.

Field work for the *Isua Multidisciplinary Research Project* in the Isukasia area of southern West Greenland, focused on the 'Earth's oldest rocks', was completed in 2001 (Fig. 1, **G**); this was the last summer of a planned series of field seasons involving a large number of Danish and international scientists.

The studies of the Vendian to early Palaeozoic rocks of Ella Ø and surroundings in North-East Greenland were continued in 2001 (Fig. 1, **J**); these are part of a continuing project investigating the passive margin succession of the Laurentian continent. Studies of the Palaeogene sediments of central East Greenland form part of regional petroleum geology investigations, and are described below.

Mineral resources

A field party visited the Qaanaaq region of North-West Greenland (Fig. 1, **M**) in 2001, focused on an assessment of the economic potential in the basement crystalline rocks as well as the overlying Mesoproterozoic sediments of the Thule Supergroup.

A regional aeromagnetic survey financed by BMP was carried out in central West Greenland covering a broad onshore and offshore region centred on Svartenhuk Halvø (Fig. 1, **C**). A total of 70 000 line km of high quality data was acquired. Regional aeromagnetic data coverage now extends from the southern tip of Greenland northwards along the entire western coast as far as latitude 72°12´N.

In conjunction with the systematic regional mapping programme in the Aasiaat region of central West Greenland, a resource assessment of the region between Nuussuaq and Maniitsoq was undertaken in 2001 (Fig. 1, **B**). Economic studies were carried out by field teams, and included investigations of the kimberlitic rocks in the Sisimiut–Kangerlussuaq region.

Other activities have included sample collections aimed at ground control of the hyperspectral data acquisition carried out in 2000 in central East and North-East Greenland. In addition, localities in South-East, South and southern West Greenland (Fig. 1, **N**) were visited in order to assess the potential for ornamental stone quarrying.

Petroleum geology

Most petroleum geology activities undertaken in 2001 were in preparation for the licensing round planned for mid-2002. The focus was mainly on promotion of the exploration opportunities in the licensing round area between 63° and 68°N, together with the launching of new seismic and geological projects.

Special mapping projects have been directed towards the Palaeogene sediments offshore southern West Greenland (Fig. 1, **F**) and the offshore area with volcanic rocks at the seabed north of latitude 68°N. A geohazard study covering the major part of the offshore licence area between 63° and 68°N was carried out for BMP in 2001.

A major source rock project involving collection and comparison of mid-Cretaceous source rocks from the interior of North America, the Canadian Arctic and the Baffin Bay – Davis Strait region was initiated. This is aimed at advancing the understanding of potential petroleum systems offshore West Greenland.

In continuation of earlier field work in the pre-basaltic, Cretaceous and Paleocene sediments of the Kangerlussuaq region in East Greenland, a field party visited the Kap Dalton and Savoia Halvø areas (Fig. 1, **I**); here the youngest pre-basaltic, and oldest post-basaltic sediments are exposed. Relationships at these localities are of particular importance for the understanding of predrift North Atlantic geology.

General scientific activities

Sampling of Holocene lake sediments has been carried out for a number of years in West Greenland, with the objective of assessing the influence of increased global warming on the sensitive Arctic ecosystems. These activities were continued in 2001, with sampling in southern West Greenland (Fig. 1, **E**). Strong local climate gradients exist between the coast and the Inland Ice, and the lakes preserve important signals relating to Holocene environmental conditions.

In order to investigate indications of thinning of the Inland Ice in South Greenland, GEUS has installed instrumentation to monitor one of the major outlet glaciers (Sermilik Bræ) from the Inland Ice in the Narsaq region (Fig. 1, **H**).

A field team collected samples of frozen peat on Carey Øer in order to study the early dispersion of heavy metals in North-West Greenland (Fig. 1, **O¹**). The same team collected submarine lake sediments in South Greenland, as part of a project to evaluate sea-level changes (Fig. 1, **O²**).

In November 2000, a major rock fall occurred on the south coast of Nuussuaq near Paatuut (Fig. 1, **D**). It was registered on seismic stations in West Greenland and at Summit on the Inland Ice, and triggered a tsunami in the Vaigat strait which caused damage at coastal settlements, but no loss of life. The Survey undertook studies of the geometry and volume of this rock fall, and assessed the risk of additional rock falls in the region.

DLC carried out seismological research in southern Nares Strait in North-West Greenland as part of a German–Canadian geoscience cruise (Fig. 1, **P**) and continued the *GLATIS* and *NEAT* projects including the monitoring of 11 temporary broad band seismological earthquake stations located throughout Greenland (Fig. 1, **Q**).

GEUS and higher education

The Survey, together with DLC, plays an active role in earth science university education with GEUS staff scientists and research professors being involved in student training for higher degrees. Close co-operation with Danish and foreign universities and research institutions is fostered, and students involved in Greenland/North Atlantic-oriented projects often take part in Survey-sponsored field work. In 2001, dissertations on Greenland-related subjects were submitted to the Universities of Copenhagen and Aarhus, Denmark for degrees at M.Sc. (Danish cand.scient.) and Ph.D. levels (see list of publications concluding this volume).

Publications

A complete list of geoscientific publications on Greenland issued by the Survey is found in the *Catalogue of Greenland publications and data*, which is also available on the web (for web address, see below). A data directory specifying the range of data and services available at the Survey covers various databases, map, sample and drill-core archives, bibliographic and library facilities, including unpublished maps and reports from the Survey's own activities and those of industry. Indexes covering projects, authors and selected topics are included in the catalogue.

The main part of the Survey's Greenland publications is printed in three series: a peer-reviewed bulletin series (Geology of Greenland Survey Bulletin), a peer-reviewed map series (Geology of Denmark and Greenland Map Series) and an open-file report series in English or Danish (Danmarks og Grønlands Geologiske Undersøgelse Rapport) that is not subject to outside refereeing or central editing. During 2001, two bulletins and 23 reports relating to Greenland geoscience were released to the public (a small number of reports are classified). In addition, two geological map sheets in the national map sheet series were published as well as two special maps. The two bulletins published are multi-article volumes containing 33 papers; in half of these GEUS staff members are authors or co-authors. About 50 scientific papers on Greenland and surrounding seas were published in 2001 in external outlets. These international publications document the results of extensive GEUS field investigations and associated activities in Copenhagen, including those of DLC and research partners in surveys and geological institutes elsewhere in the world (see list of publications concluding this volume).

An important role of the Survey is to provide up-to-date geoscientific and legislatory information to the petroleum and mining industries. Hence two newsletters, the GHEXIS Newsletter and MINEX, launched over a decade ago, are published jointly by GEUS and BMP. One issue of GHEXIS and three issues of MINEX were published in 2001.

The demand for digital versions of geoscientific data is increasing rapidly, and the Survey is meeting this challenge by releasing geological information, maps and data on CD-ROM. Three CD-ROMs were issued in 2001. The GHEXIS and MINEX newsletters have been available on the GEUS and BMP websites for several years; however, two new sites were developed in 2001, GHEXIS Online and MINEX Online (for web addresses, see below). GHEXIS Online is fully developed and now provides information on licensing policy, geology, hydrocarbon potential, available data, and operational conditions in connection with the licensing round offshore West Greenland in 2002, in addition to the GHEXIS Newsletter. MINEX Online also provides information on licensing policy and operational conditions.

The Survey's publication web addresses are:
GEUS publications online service – www.geus.dk/publications/publ-uk.htm
Catalogue of Greenland publications – www.geus.dk/publications/cat-publ-greenland-uk.htm
GHEXIS Online – www.geus.dk/ghexis
MINEX Online – www.geus.dk/minex

Author's address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *ks@geus.dk*

Precambrian geology of the northern Nagssugtoqidian orogen, West Greenland: mapping in the Kangaatsiaq area

Jeroen A.M. van Gool, G. Ian Alsop, Uni E. Árting, Adam A. Garde, Christian Knudsen, Adam W. Krawiec, Stanislaw Mazur, Jeppe Nygaard, Sandra Piazolo, Christopher W. Thomas and Kristine Thrane

The Nagssugtoqidian orogen and its transition into the Rinkian orogen to the north were the main focus of the field activities of the Geological Survey of Denmark and Greenland (GEUS) in West Greenland in the summer of 2001. This work was carried out within the framework of the Survey's three-year programme of bedrock mapping and mineral resource evaluation to enhance the understanding of the Archaean and Palaeoproterozoic crustal evolution in the transition zone between the Nagssugtoqidian and Rinkian orogens (Fig. 1). The work in the field season of 2001 comprised geological mapping of the 1:100 000 Kangaatsiaq map sheet described in this paper (Fig. 2), an investigation of the supracrustal rocks at Naternaq / Lersletten (Østergaard *et al.* 2002, this volume), a geochronological reconnaissance of the southern Rinkian orogen in the northern Disko Bugt region (Garde *et al.* 2002, this volume), a resource evaluation of the Nagssugtoqidian orogen (Stendal *et al.* 2002, this volume), a synthesis and interpretation of geophysical data of the central part of the Nagssugtoqidian orogen (Nielsen *et al.* 2002, this volume) and a report on investigations of the kimberlites and related intrusive rocks in the southern Nagssugtoqidian orogen and its foreland (Jensen *et al.* 2002, this volume).

The present investigations build on recent previous activities in the region. The Disko Bugt project of the former Geological Survey of Greenland investigated the geology and evaluated the resource potential of the southern part of the Rinkian orogen between Nuussuaq and Jakobshavn Isfjord from 1988 to 1992 (Fig. 1; Kalsbeek 1999). The Danish Lithosphere Centre (DLC) led a research project from 1994–1999 into the tectonic evolution of the Nagssugtoqidian orogen concentrating on the southern and central segments of the orogen between Sukkertoppen Iskappe and Nordre Strømfjord (Marker *et al.* 1995; van Gool *et al.* 1996, in press; Mengel *et al.* 1998; Connelly *et al.* 2000). Previous activity in the area between Nordre Strømfjord and Jakobshavn Isfjord (Fig. 1) included reconnaissance mapping by Noe-Nygaard & Ramberg (1961), 1:250 000 scale mapping by Henderson (1969), and visits to key localities during the DLC project (Marker *et al.* 1995; Mengel *et al.* 1998) from which a few reconnaissance age determinations are known (Kalsbeek & Nutman 1996). Most of this area was known from coastal exposures, while map information for large parts of the inland areas was based only on photogeological interpretation. The mineralised parts of the Naternaq supracrustal belt were investigated in detail by Kryolitselskabet Øresund A/S from 1962–1964 (Keto 1962; Vaasjoki 1965). Immediately south of latitude 68°N the 1:100 000 scale Agto (Attu) map sheet was published by Olesen (1984), and the adjacent Ussuit map sheet to the east is in preparation (Fig. 1). Mapping in 2001 concentrated on the Kangaatsiaq map sheet area and the Naternaq area (Østergaard *et al.* 2002, this volume), while mapping activity for 2002 is planned between Naternaq and Jakobshavn Isfjord (Fig. 1).

The field work in 2001 was supported by M/S *Søkongen* as a floating base from which field camps were established. The shoreline exposures are excellent and the many islands and extensive fjord systems in the map area provide easy access. Limited helicopter support was available for establishment of a few inland camps and reconnaissance in areas far from the coast.

The Nagssugtoqidian orogen

The Nagssugtoqidian orogen is a 300 km wide belt of predominantly Archaean gneisses which were reworked during Palaeoproterozoic orogenesis. It is characterised by E–W-trending kilometre-scale folds and ENE–WSW-trending linear belts. It is divided into three tectonic segments: the southern, central and

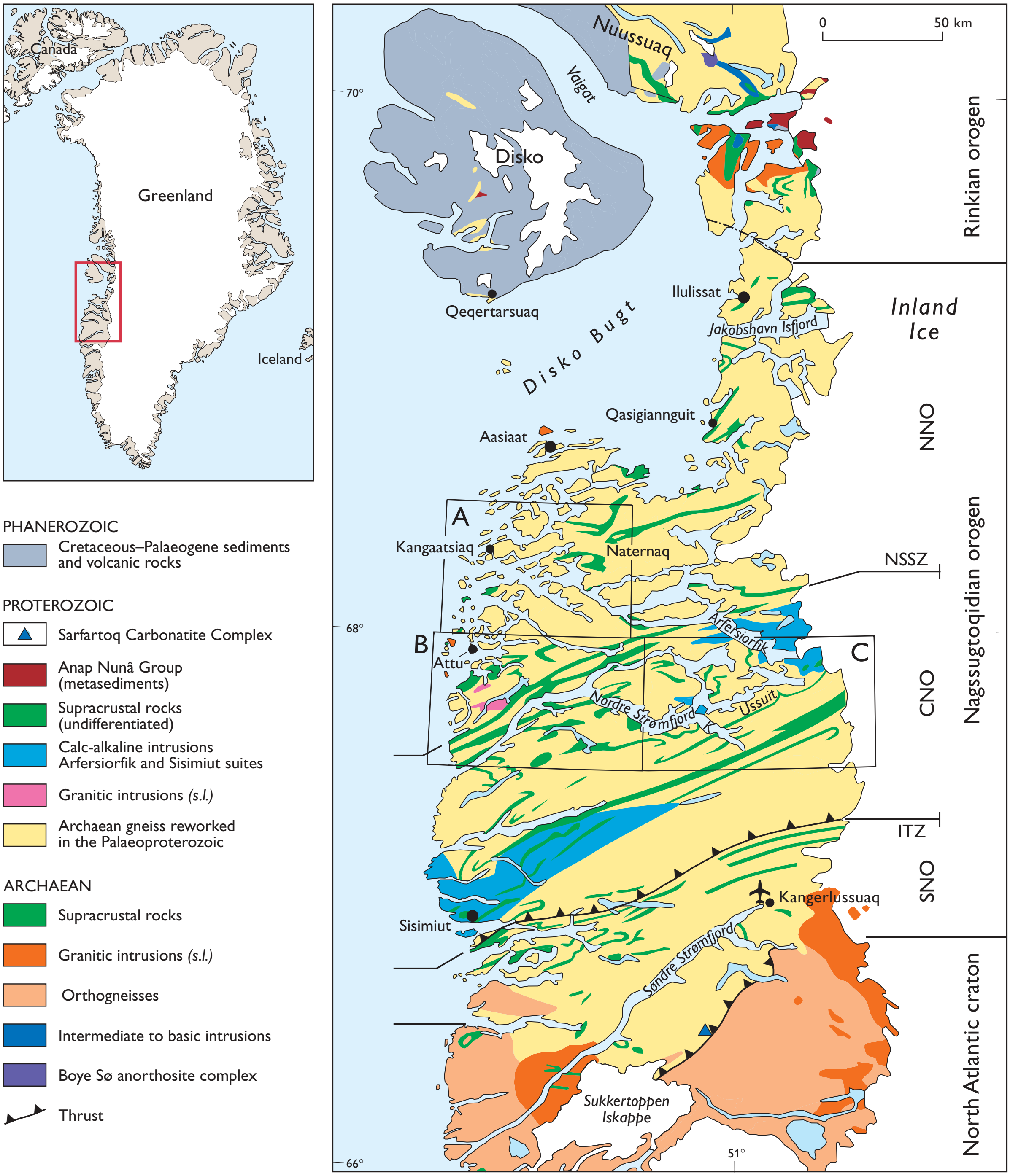


Fig. 1. Geological map of southern and central West Greenland, showing the divisions of the Nagssugtoqidian orogen and the boundaries with the North Atlantic craton to the south and the Rinkian orogen to the north. Outlined areas indicated **A**, **B** and **C** are, respectively, the Kangaatsiaq, Agto (Attu) and Ussuit 1:100 000 map sheets. **ITZ**: Ikertôq thrust zone. **NSSZ**: Nordre Strømfjord shear zone. **SNO**, **CNO** and **NNO** are, respectively, the southern, central and northern Nagssugtoqidian orogen. Modified from Escher & Pulvertaft (1995) and Mengel *et al.* (1998).

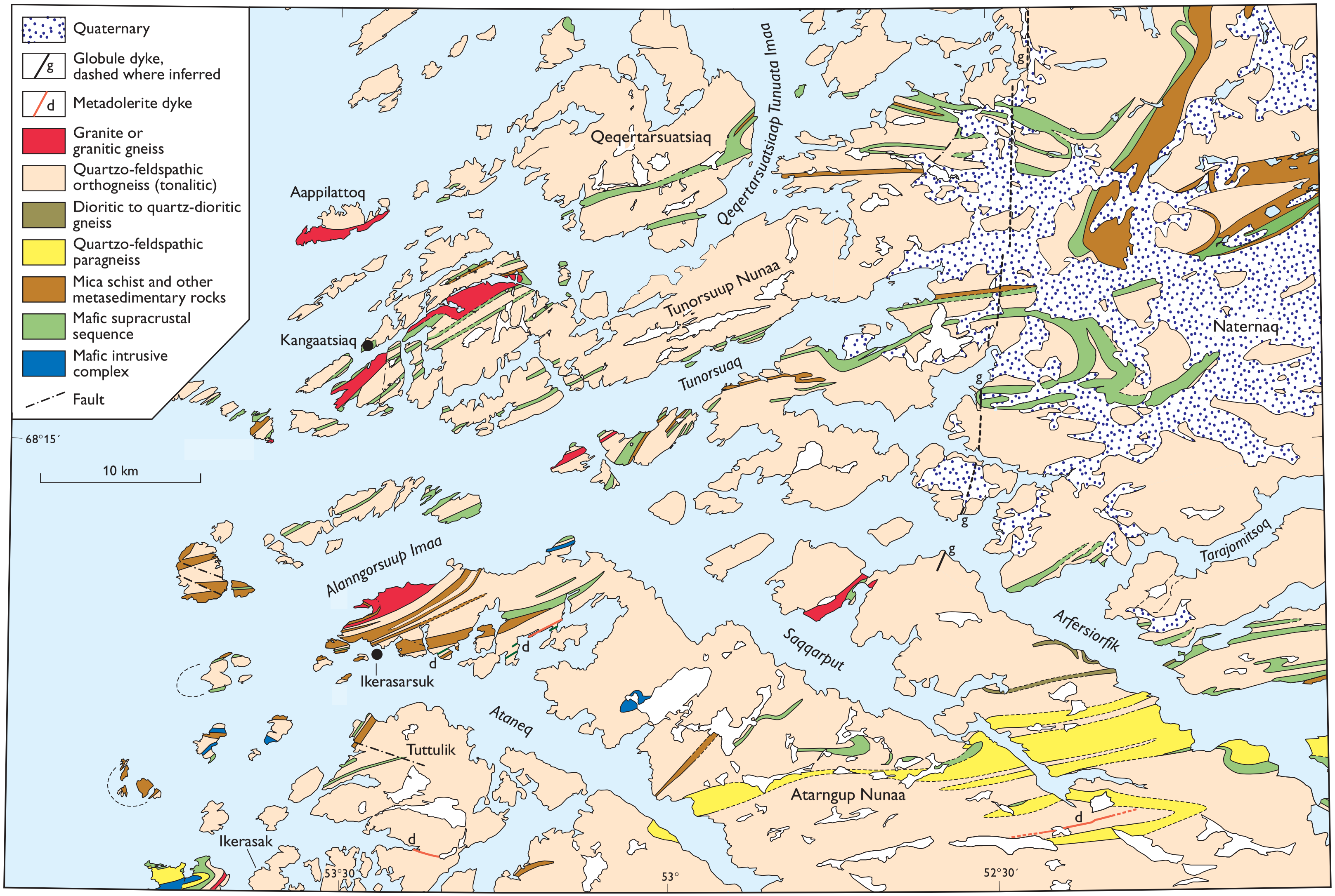


Fig. 2. Simplified geology of the Kangaatsiaq map sheet. For location, see Fig. 1, frame A.

northern Nagssugtoqidian orogen (SNO, CNO and NNO, Fig. 1; Marker *et al.* 1995). These segments are interpreted by van Gool *et al.* (2002) as, respectively, a southern parautochthonous foreland zone, a central collisional core of the orogen and a northern transition zone to the Rinkian orogen. Archaean granulite-facies gneisses of the North Atlantic Craton, which forms the southern foreland, were reworked in the SNO at amphibolite facies during south-directed thrusting and folding. The CNO comprises, besides Archaean gneisses, two main bodies of Palaeoproterozoic calc-alkaline intrusive rocks: the Sisimiut charnockite suite in the south-west and the Arfersiorfik intrusive suite in the north-east (Kalsbeek & Nutman 1996; Whitehouse *et al.* 1998), which are interpreted as remnants of magmatic arcs associated with subduction (Kalsbeek *et al.* 1987). Palaeoproterozoic metasedimentary rocks are known from narrow belts in the CNO and in the northern part of the SNO. In the northern part of the CNO they are intruded by quartz diorite and tonalite of the Arfersiorfik intrusive suite (Kalsbeek & Nutman 1996; van Gool *et al.* 1999). This association of Palaeoproterozoic intrusive and supracrustal rocks was interleaved with Archaean gneisses by NW-directed thrust stacking during early stages of collision (van Gool *et al.* 1999, 2002; Connelly *et al.* 2000). Thrust stacks and associated fabrics were subsequently folded in several generations of folds, the latest forming shallowly east-plunging upright folds on the scale of tens of kilometres. The CNO is largely at granulite facies, with the exception of its north-eastern corner which is at amphibolite facies. Its northern boundary is formed by the Nordre Strømfjord shear zone (Fig. 1; Marker *et al.* 1995; Hanmer *et al.* 1997).

The NNO is the least known part of the orogen. Tonalitic orthogneisses of Archaean age are interleaved with supracrustal rocks of both volcanic and sedimentary origin, most of which form belts up to 500 m wide (Mengel *et al.* 1998). Supracrustal rocks are less common than in the CNO, but the up to 2 km wide Naternaq supracrustal belt in the north-east is one of the largest coherent supracrustal belts in the orogen (Fig. 1). The main deformational features are a regional foliation, large-scale ENE–WSW-trending folds and several ductile high-strain zones, both steeply and shallowly dipping. The metamorphic grade is predominantly amphibolite facies, but increases southwards to granulite facies around Attu (Mengel *et al.* 1998; Connelly *et al.* 2000). $^{40}Ar/^{39}Ar$ age determinations on hornblende from the NNO indicate that Nagssugtoqidian metamorphic temperatures of at least 500°C prevailed as far north as Ilulissat (Willigers *et al.* 2002). Nagssugtoqidian deformation in the Nordre Strømfjord shear zone at the southern boundary of the NNO resulted in a penetrative gneissic high-grade fabric, large-scale upright folds and localised shear zones, as seen in the deformation of Palaeoproterozoic intrusive and sedimentary rocks (Hanmer *et al.* 1997; Mengel *et al.* 1998; van Gool *et al.* 2002). It is not clear to what extent the structures and lithologies in the NNO can be correlated with those in the Nordre Strømfjord shear zone or further south.

Geology of the Kangaatsiaq area

The Kangaatsiaq map sheet covers a large part of the western half of the NNO (Figs 1, 2). Supracrustal rocks were previously recognised in a zone trending from the north-eastern to the south-western quadrant of the map where they outline major fold structures. The south-central and south-eastern parts were indicated as homogeneous orthogneiss due to lack of observations (Escher 1971). A quartz-diorite body was distinguished in the south-eastern part of the map area by Henderson (1969). A few minor occurrences of granite were known, of which that at Naternaq is the largest (Figs 1, 2).

During field work in 2001, twelve lithological units were distinguished, of which several were previously unknown. Ten of these rock types are represented on the map in Fig. 2, while occurrences of the others are too small for the scale of the map. Relative age relationships were established for most of the rock types but absolute ages are still largely unknown. The few available geochronological data are discussed in a separate section below. The Naternaq supracrustal sequence is described by Østergaard *et al.* (2002, this volume). The other lithological units are described below from oldest to youngest.

Mafic intrusive complexes

Dismembered, layered mafic to ultramafic intrusive complexes are dominated by medium- to coarse-grained, massive to moderately foliated, homogeneous amphibolite, but locally igneous layering is preserved (Fig. 3). The rocks contain hornblende and plagioclase, with or without clinopyroxene, orthopyroxene, biotite, quartz or garnet. The protolith rock types include gabbro, gabbro-norite, ultramafic rocks (mostly pyroxenite and hornblendite), and rarely thin anorthosite sheets occur. This association occurs within the domi-

Fig. 3. Well-preserved metamorphosed layered gabbro in an outcrop of the mafic intrusive complex on the island of Ikerasak in the south-western corner of the map area.

nant tonalitic orthogneisses mainly as lenses up to tens of metres in diameter, but also forms larger bodies up to 2 km across. The rocks are cut by tonalitic and granitic intrusive sheets and veins and occur often strongly agmatised. The mafic lenses contain remnants of a foliation and subsequent folding, which predate the intrusion of the regional orthogneisses. The mafic intrusive complexes are most abundant in the southern part of the map area.

Mafic supracrustal sequences

Thinly layered mafic to intermediate sequences with thin felsic intercalations are interpreted as supracrustal, predominantly meta-volcanic sequences (Fig. 4). They are layered on a millimetre- to centimetre-scale and contain variable amounts of hornblende and plagioclase, with or without clinopyroxene, biotite, garnet and quartz. Isolated, thin quartzo-feldspathic layers, *c.* 5 to 20 cm thick, are interpreted as psammitic incursions in which presumed granule and pebble-sized detrital grains were observed north-east of Kangaatsiaq. These rocks are intruded by the dominant tonalitic gneiss and occur both as up to 500 m thick, laterally extensive sequences and as smaller xenoliths. In several cases the boundary between the tonalitic gneiss and the supracrustal sequence is tectonically reworked. The age relationship between the mafic supracrustal and mafic intrusive rocks could not be established. The mafic supracrustal rocks are common in a *c.* 20 km wide belt that extends from the south-

Fig. 4. Mafic supracrustal sequence consisting of layered (meta-volcanic) amphibolite alternating with thin layers of psammite and quartzite. Outcrop is located 18 km south-east of Kangaatsiaq. Lens cap, centre, is 7 cm in diameter.

western to the north-eastern corner of the map area (Fig. 2). The mafic supracrustal sequences contain rare, up to 5 m thick layers of medium-grained, forsterite-humite marble or medium- to coarse-grained, diopside-rich calc-silicate rocks.

Mica schist

Sequences of mica-rich rocks vary from biotite-rich semi-pelitic schists to biotite, garnet- and sillimanite-bearing schists and gneisses, which are intercalated with thin quartzo-feldspathic layers and some quartzite. In the northern part of the area the gneisses locally contain muscovite, kyanite or cordierite. The schists are generally associated with mafic supracrustal rocks, and rarely form isolated occurrences. They are especially abundant in a belt in the central part of the map area and in the Naternaq area (Østergaard *et al.* 2002, this volume).

Quartzo-feldspathic paragneisses

Quartzo-feldspathic gneisses form 2–3 km thick sequences in the south-eastern part of the map area where they are interpreted as metapsammitic rocks. These grey, medium-grained paragneisses are rather homogeneous, often quartz-rich and poor in biotite, and may contain abundant small (1–2 mm) garnets. Local rounded quartz and feldspar grains up to 1 cm across are interpreted as pebbles. The quartzo-feldspathic paragneisses are interlayered with 5–100 cm wide amphibolite layers, which are probably of volcanic origin. Slightly discordant, deformed mafic dykes (see below) have also been observed. Rare, biotite-rich micaceous layers locally contain garnet and sillimanite. Contact relationships with the surrounding grey orthogneisses and their relative ages are uncertain, and locally these two lithological units can be difficult to distinguish in the field.

Dioritic to quartz-dioritic gneiss

This unit consists of medium-grained, uniform, dark-grey migmatitic or agmatitic orthogneisses, containing hornblende, plagioclase, quartz and minor biotite. It occurs mainly as small lenses in the tonalitic orthogneiss unit and only seldom forms larger, mappable bodies in the south. The largest bodies and layers of quartz-diorite are up to 50 m wide and occur in the Arfersiorfik area (Fig. 2). Contact relationships with the tonalitic gneisses are not clear everywhere, but a few dioritic bodies occur as xenoliths. None of the quartz-diorite bodies have so far been correlated with the Palaeoproterozoic Arfersiorfik quartz diorite (Kalsbeek *et al.* 1987) that occurs in the eastern end of Arfersiorfik and Nordre Strømfjord (Fig. 1). However, this correlation cannot be ruled out for at least some of the occurrences, and geochemical analyses and possibly geochronology will be used to test this. The large body of quartz-dioritic gneiss north and south of the fjord Tarajomitsoq in the eastern part of the map area, indicated by Henderson (1969), could not be confirmed.

Fig. 5. Tonalitic gneiss with amphibolite lenses, presumed to be mafic dyke remnants. Pink granitic veins give the rock a migmatitic texture. Near Alanngorsuup Imaa.

Tonalitic and associated quartzo-feldspathic orthogneiss

The predominant orthogneiss unit comprises a wide range of lithologies, which in most cases lack sharp mutual contacts and cannot be mapped out as separate units. Grey, fine- to medium-grained biotite-bearing tonalitic gneiss predominates (Fig. 5). Tonalitic gneiss with abundant medium-grained hornblende occurs commonly in the proximity of mafic inclusions, and a plagioclase-porphyric, hornblende-bearing tonalitic gneiss, characterised by up to 2 cm large clusters of hornblende occurs mainly in the north-western part of the map area. In places, the orthogneiss is migmatitic, containing up to 30% coarse-grained, K-feldspar-rich melt veins up to 5 cm thick (Fig. 5). Another less common melt phase intruding all varieties of the grey orthogneiss consists of leucocratic, white, medium- to coarse-grained granodiorite to granite and occurs predominantly in the south. It forms veins and larger coherent bodies up to one metre wide and can locally form up to 30% of the rock volume.

High-grade, mafic dyke relics

These metadolerite dyke relics are homogeneous, fine- to medium-grained, and consist of hornblende, plagioclase and clinopyroxene, with or without orthopyroxene, biotite and quartz. Garnet is seen rarely at the margins. Commonly the dykes are intensely deformed, foliated and lineated, boudinaged, or transformed to mafic schlieren which can be difficult to identify as dykes (Fig. 5). The less deformed dykes are commonly about 20 cm thick, but can reach 50 cm. Discordant relationships can be preserved in areas of low strain, but angles of discordance are always small. The dykes are widespread and locally form up to 25% of the rock volume, but they do not form a map unit that can be depicted on the scale of Fig. 2. They were commonly observed in the southern part of the map area, where they form dense swarms in the grey orthogneisses (Fig. 6).

Granite and granitic gneiss

Numerous small and large intrusive bodies of granite with a wide range of lithological appearances and different states of deformation were mapped. Coarse-grained, homogeneous pink granite predominates and may grade into megacrystic granite, sometimes with rapakivi-textures, pink microgranite, or pegmatite.

Fig. 6. Cliff exposing orthogneisses invaded by a dyke swarm which is boudinaged and folded. Vertical dark streaks are caused by water flowing over the cliff. Height of cliff is about 50 m. The outcrop is located at the southern boundary of the map area, 6 km east of the fjord Ataneq.

White, leucocratic granite is also observed. Based on their deformational state and contact relationships the granite bodies fall into two main categories (not distinguished on the map): foliated granites with gradational boundaries to their host rocks, and relatively undeformed granites with obvious intrusive contacts. The contact zones between tonalitic orthogneiss and the granites can be tens to hundreds of metres wide, beginning with a few thin granitic veinlets in the orthogneiss, grading into granite or granitic gneiss with abundant orthogneiss inclusions, and ending with almost inclusion-free granite. The gneissic fabric in the inclusions is commonly cut by the granites, which may nevertheless themselves be strongly foliated.

Pegmatite

Several generations of pegmatite have been observed, often cross-cutting and in different stages of deformation. They are commonly coarse-grained, rich in pink K-feldspar, and contain quartz and plagioclase with or without biotite. In general, two main types can be distinguished. The older pegmatites are slightly discordant, commonly irregular in shape and can be folded and strongly sheared, resulting in porphyroclastic, mylonitic textures. They appear to be associated with the granitic gneisses described above. Some of these pegmatites can be shown to be syn-kinematic with the latest fold phase (see below). The second, younger group consists of conjugate sets of late, straight-walled pegmatites. They are undeformed and commonly associated with steep brittle faults that have offsets which are consistent with north–south compression. These pegmatites may be younger than the metadolerite dykes described below.

Metadolerite dykes

Massive, 1–20 m wide metadolerite dykes occur mainly in the southern part of the map area. They cut the regional gneissic fabric and most have E–W trends. Foliation is only well developed in the dyke margins although a weak linear fabric can be observed locally in the unfoliated cores. The dykes have metamorphic mineral assemblages of fine- to medium-grained hornblende, plagioclase and clinopyroxene, with or without orthopyroxene, garnet and rarely biotite. In contrast to the older foliated dyke remnants they always occur as isolated bodies.

Globule dyke

A single, N–S-trending, 20–50 m wide composite dolerite dyke with unusual globular structures was described by Ellitsgaard-Rasmussen (1951). The name for the dyke was based on the local presence of spheres with igneous textures that comprise plagioclase and pyroxene phenocrysts in the core, surrounded by glassy mantles. Several locations were revisited and showed the dyke to be undeformed and to consist of a *c.* 10 m thick central dyke with thinner multiple intrusions on both sides which have glassy, chilled margins. The dyke is exposed in a few outcrops along a 60 km long stretch from the entrance of the fjord Arfersiorfik northwards to the coast east of Aasiaat. On the aeromagnetic map of the NNO (Thorning 1993) this trace is clearly visible, with several right-lateral steps as depicted in Fig. 2.

Geochronology

U-Pb zircon age determinations have been carried out on six samples from the map area (Kalsbeek & Nutman 1996). Archaean ages in the range 2.7–2.8 Ga were derived from four biotite orthogneiss samples. A porphyric granite yielded zircons of *c.* 2.7 Ga, indistinguishable in age from a gneiss which forms the host rock at the same location. It is uncertain whether these two lithologies are indeed of approximately the same age, or whether the granite contains locally derived inherited zircons. One of two samples from the Naternaq supracrustal sequence contained Proterozoic detrital zircons, suggesting that at least part of the sequence is of Proterozoic age (Østergaard *et al.* 2002, this volume).

Kalsbeek *et al.* (1984) derived an Archaean Pb-Pb isochron age of 2653 ± 110 Ma for a granite that is intrusive into the regional gneisses just south of the map area. An undeformed granite sampled near Aasiaat just north of the map area yielded an intrusive age of 2778 $^{+7}_{-3}$ Ma (TIMS U-Pb on zircon, Connelly & Mengel 2000). Preliminary LAM-ICPMS Pb-Pb reconnaissance analyses on detrital zircons from a felsic layer of a dominantly mafic supracrustal sequence north-east of Kangaatsiaq have yielded Archaean ages.

The available isotope data establish that the regionally dominant tonalitic gneisses have Archaean protolith ages, and that at least some granites in the NNO are also Archaean. The ages of the younger pegmatites and of the metadolerite dykes are at present uncertain. A regional dating programme of rocks in the northern Nagssugtoqidian orogen and southern Rinkian orogen is underway to establish the ages of the main lithologies and tectonic events (Garde *et al.* 2002, this volume).

Metamorphism

The map area is dominated by upper amphibolite facies, medium-pressure mineral assemblages, but has been affected by granulite facies metamorphism south of the fjords Arfersiorfik and Alanngorsuup Imaa (Fig. 2). Mineral assemblages in metapelites include garnet-biotite-sillimanite in most of the area, with minor kyanite or cordierite observed locally north-east of Kangaatsiaq. Muscovite is stable in the northernmost part of the map area. Partial melt veins occur in most of the region giving the gneisses a migmatitic texture. Relic granulite facies rocks occur as patches in the south within areas of amphibolite facies. The granulite facies grade is reflected in the weathered appearance of the rocks, but orthopyroxene is seldom visible in hand specimen. It does, however, appear as relics in thin section. The age of the granulite facies metamorphism is uncertain, but Palaeoproterozoic rocks in the nearby Nordre Strømfjord shear zone (Fig. 1) are also at granulite facies, and were retrogressed to amphibolite facies in high-strain zones during a late phase of Nagssugtoqidian orogenesis.

Structure

Detailed field observations combined with the map pattern show that at least four generations of regionally penetrative structures are recorded in the dominant orthogneisses, while an even older penetrative planar fabric and isoclinal folds are preserved in mafic inclusions. The regional gneissosity dips to the NNW or SSE at steep to moderate angles, and carries a subhorizontal, ENE–WSW-trending mineral grain lineation or aggregate lineation. It is a high-temperature fabric, and commonly migmatitic veins are developed parallel to it. Locally the gneissosity is axial planar to isoclinal, often rootless, folds. The main gneissosity is a composite fabric, heterogeneously developed either progressively over an extended period of time or in several phases before and after intrusion of the mafic dyke swarm in the south.

At least two phases of folding affected the area. The early isoclinal folds have no consistent orientation and may represent several generations of folds, as reported from the Attu area by Sørensen (1970) and Skjernaa (1973). Map-scale isoclinal folds are most obvious in the north-eastern and south-western map quadrants, outlined by the supracrustal sequences. At several locations the isoclinal folding resulted in interleaving of ortho- and paragneisses. It is also possible that some interleaving occurred by thrust repetition, as reported from the Attu area (Skjernaa 1973) and from south of the Nordre Strømfjord shear zone (van Gool *et al.* 1999), but so far no unambiguous evidence for thrust repetition has been found in the map area. Shear zones are uncommon and of local extent, mainly associated with the reworking of intrusive contacts between supracrustal rocks and orthogneisses and lacking consistent kinematic indicators. Their relative age with respect to the fold phases is uncertain.

Parasitic folds associated with the youngest, major phase of upright folds are sub-horizontal to moderately plunging, with predominantly WSW-plunging axes. Near the hinges of kilometre-scale folds the parasitic folds are commonly steeply inclined, plunging to the south. Mineral lineations are commonly parallel to sub-parallel with the axes of parasitic folds. Sets of late, steeply dipping conjugate fractures trend NE–SW and NW–SE and some of these are filled with a pegmatitic melt phase.

Summary and conclusions

The Kangaatsiaq region in the northern Nagssugtoqidian orogen predominantly consists of Archaean orthogneisses. It includes a major ENE–WSW-trending belt with abundant supracrustal rocks, which runs from south of Kangaatsiaq to the southern part of Naternaq. A second, previously unknown but extensive belt of quartzo-feldspathic paragneisses, presumably of Archaean age, occupies part of the south-eastern corner of the map area.

The main events in the geological evolution of the area comprise:

1. intrusion of mafic igneous complexes and deposition of mafic and associated supracrustal rocks;
2. formation of a foliation and isoclinal folds;
3. intrusion of the main tonalitic and associated granitoid rocks;
4. formation of the regional gneissic fabric;
5. intrusion of a mafic dyke swarm in the south;
6. further deformation, probably associated with isoclinal folding and intensification of the regional gneissosity;
7. intrusion of granite and pegmatite;
8. formation of a foliation and gneissosity in the granites, in part during their intrusion and associated with upright folding;
9. intrusion of the E–W-trending, isolated metadolerite dykes;
10. formation of upright brittle fractures during intrusion of pegmatite.

At present, an evaluation of the tectonic evolution of the Kangaatsiaq area in a regional perspective is difficult, since the absolute ages of several lithological units and deformational events are still unknown. It is uncertain to what extent the Palaeoproterozoic tectonic events known from south of the Nordre Strømfjord shear zone can be correlated with those of the Kangaatsiaq area. The map area lacks the abundance of Proterozoic supracrustal sequences intruded by quartz-diorite and the shear zones associated with their emplacement, that are typical for the central Nagssugtoqidian orogen (van Gool *et al.* 1999). The most likely candidate for a Palaeoproterozoic supracrustal sequence in the map area is the Naternaq supracrustal belt. Furthermore, the shear zones in the Kangaatsiaq area are not of regional extent. The lack of consistent kinematic indicators in the shear zones suggests that deformation may have been dominated by pure shear. Coincidence of the orientation and style of the youngest upright, E–W-trending folds in the Kangaatsiaq area with similar structures of Palaeoproterozoic age to the south (Sørensen 1970; Skjernaa 1973; van Gool *et al.* 2002) and in the Disko Bugt area to the north (several papers in Kalsbeek 1999) was suggested by Mengel *et al.* (1998) as a possible indication for direct correlation.

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Authors' addresses

J.A.M.v.G., A.A.G., C.K., J.N., S.P. & K.T., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*. E-mail: *jvg@geus.dk*

G.I.A., *School of Geography & Geosciences, University of St. Andrews, St. Andrews, Fife, KY16 9AL, UK.*

U.E.Á., *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.*

A.W.K., *Department of Geological Sciences, University of Texas at Austin, Austin, TX, 78712, USA.*

S.M., *Institute of Geological Sciences, University of Wroclaw, Pl. Maxa Borna 9, 50–204 Wroclaw, Poland.*

C.W.T., *British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK.*

The Precambrian supracrustal rocks in the Naternaq (Lersletten) and Ikamiut areas, central West Greenland

Claus Østergaard, Adam A. Garde, Jeppe Nygaard, Jette Blomsterberg, Bo Møller Nielsen, Henrik Stendal and Christopher W. Thomas

Naternaq, or Lersletten, in central West Greenland is an extensive Quaternary outwash plain characterised by light grey, silty sediments. Scattered low hills with outcrops of crystalline Precambrian basement rocks protrude from the outwash plain and form the northern part of the Nagssugtoqidian orogen (e.g. Connelly *et al.* 2000). The prominent Naternaq supracrustal belt, at least 25 km long and up to *c.* 2 km wide, occurs along the north-western margin of Lersletten, bordered on both sides by Archaean orthogneisses and granitic rocks; the supracrustal rocks outline a major fold structure with an irregular and sporadically exposed hinge zone (Fig. 1). The supracrustal rocks, including the fold closure, exhibit a negative signature on the regional aeromagnetic map (Fig. 2). The belt is known for its disseminated and massive iron sulphide mineralisation with minor copper and zinc, which is common in the south-eastern part of the belt.

Study of the Naternaq supracrustal belt was an important objective of the Survey's field work in 2001 (Stendal *et al.* 2002, this volume). Boundaries, contact relationships and principal rock types were established in the western part of the belt (van Gool *et al.* 2002, this volume). Well-exposed parts of the belt were mapped in detail (Fig. 3), and the main lithologies and their mineralisations were investigated and sampled. Preliminary results of the mapping are presented in this report, together with a brief discussion of the depositional environment, likely age, and mineralisation processes of the supracrustal sequence. Large tracts of supracrustal rocks in the adjacent Ikamiut area (Fig. 1) and near Qasigiannguit/Christianshåb some 50 km further to the east may once have been contiguous with the Naternaq supracrustal belt, but further mapping is required to substantiate this.

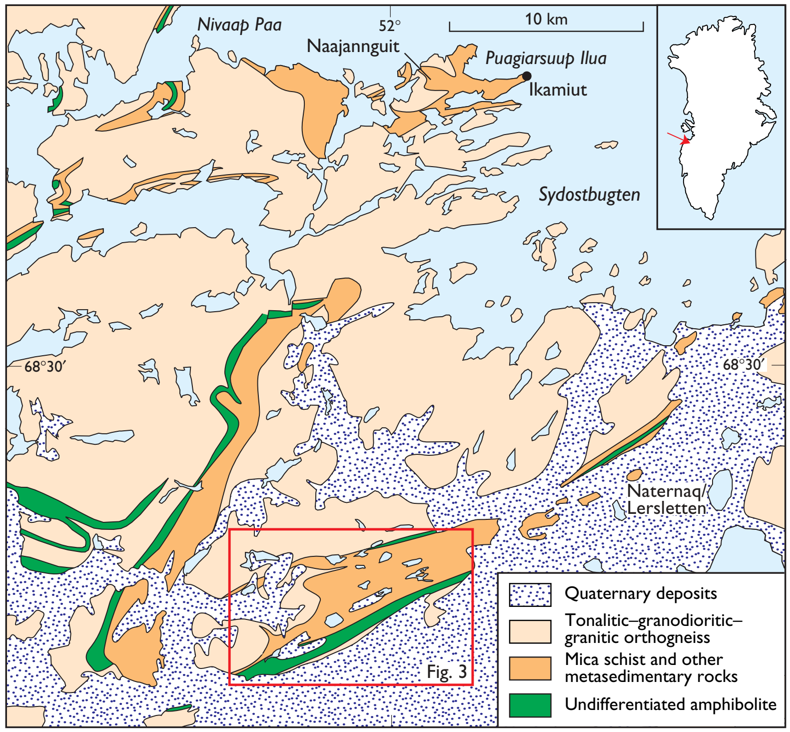
Previous work

The earliest coastal geological reconnaissance in central West Greenland was carried out by Noe-Nygaard & Ramberg (1961), who noted the obvious supracrustal origin of garnet-mica schists at Ikamiut and in the Qasigiannguit area. The Naternaq supracrustal belt itself was outlined by Henderson (1969) on his preliminary map of the Egedesminde–Christianshåb area.

Kryolitselskabet Øresund A/S (KØ) undertook a major base metal exploration programme in the region in 1962–1964, which concentrated on the most extensively mineralised southern part of the Naternaq supracrustal belt, following the discovery of the mineralisation in 1962 (Keto 1962; Vaasjoki 1965). General geological, electromagnetic, magnetic and gravimetric ground surveys were carried out which helped define drilling targets characterised by anomalous electromagnetic signatures and Cu-Zn geochemical anomalies. These were drilled and trenched, and indicate a sulphide resource of 2.4–4.8 million tonnes grading 30–35 wt% Fe and locally up to 2.7% Cu and 3.75% Zn (Vaasjoki 1964, 1965). In 1978 a regional airborne magnetic and electromagnetic survey by KØ covered parts of central West Greenland including Naternaq (Peltonen 1978). In 1990–1993 Nunaoil A/S (now Nuna Minerals A/S) prospected at Naternaq with ground geophysical VLF and magnetic surveys, as well as a regional sediment sampling programme (Gowen 1992; Sieborg 1992; Grahl-Madsen 1994). Nunaoil also re-analysed the KØ drill cores for gold, and found Au values of up to 0.6 ppm over 0.35 m. These exploration programmes only paid limited attention to the genesis and structural evolution of the host rocks and their mineralisation processes.

In 1992 a high resolution aeromagnetic survey was carried out in central West Greenland by Geoterrex Ltd (Canada), financed by Danish and Greenlandic sources (Thorning 1993). Part of the resulting aeromagnetic map is shown in Fig. 2. A regional interpretation of the aeromagnetic data by Schacht (1992) distinguished several areas of supracrustal rocks, including those at Naternaq, as well as other geological features. The Lersletten supracrustal belt stands out as a prominent magnetic low, whereas orthogneisses generally produce banded

Fig. 1. Geological sketch map of the Naternaq–Ikamiut area based on field work in 2001 and reconnaissance data from Henderson (1969). The inset map shows the position in West Greenland (**arrow**), and the location of Fig. 3 is shown by a **red frame**.



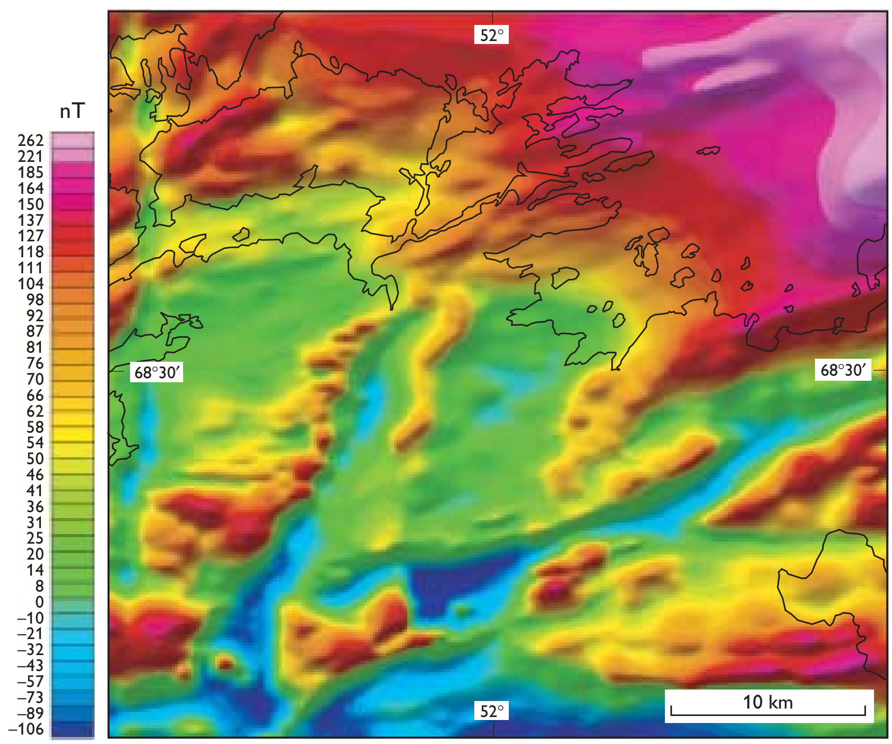


Fig. 2. Magnetic total-field intensity map with shaded relief of the Naternaq–Ikamiut area, the same area as shown on Fig. 1. The magnetic patterns clearly reflect the major fold structure and lithologies evident from Fig. 1. The shading was undertaken with an inclination of 20° and illumination from 330°. Data from the *Aeromag 1992* programme (Schacht 1992; Thorning 1993).

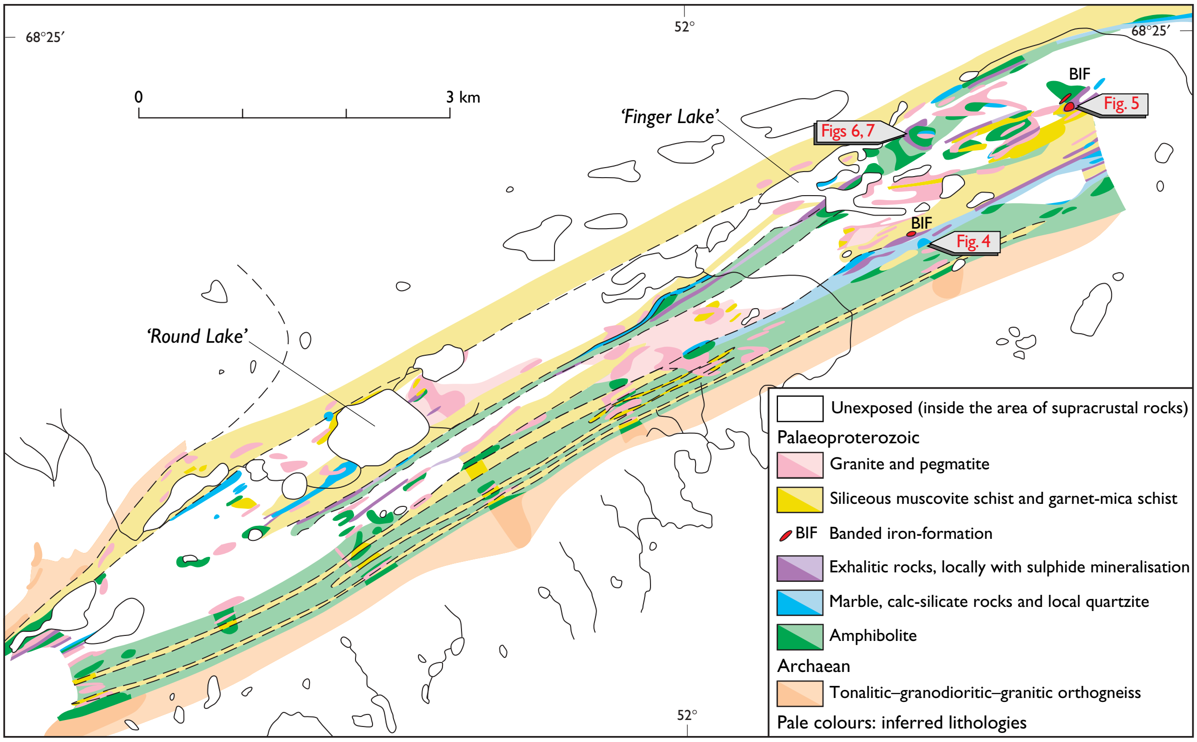


Fig. 3. Detailed geological map from the southern part of the Naternaq supracrustal belt. 'Round Lake' and 'Finger Lake' are informal KØ names (see the main text). The position in the Naternaq area is shown on Fig. 1. Positions of photographs (Figs 4–7) are shown by **arrows**.

linear anomalies of intermediate amplitude. Amphibolite, with intermediate to very high amplitudes, can be difficult to distinguish from orthogneiss. They are both visible as clusters of high amplitude anomalies with half-widths in the order of 1–2 km. Mica schists produce banded linear zones with low magnetic response, whereas granites produce equidimensional, homogeneous zones with high response.

Sparse geochronological data from the Naternaq area suggest that the Naternaq supracrustal belt itself is of Palaeoproterozoic age, whereas the supracrustal rocks at Ikamiut are probably Archaean. Kalsbeek (1993) and Kalsbeek & Taylor (1999) obtained a Palaeoproterozoic Rb-Sr whole-rock age from metasedimentary rocks at Ikamiut which shows that this area was reworked during the Nagssugtoqidian orogeny, but the inferred initial $^{87}Sr/^{86}Sr$ ratio is so high that these rocks were interpreted as Archaean. Ion probe U-Pb age determinations carried out by the Danish Lithosphere Centre in the mid-1990s of a few zircons from one of the granodioritic to granitic orthogneiss bodies that appear to cut the supracrustal belt indicated an emplacement age between 2750 and 2900 Ma (Kalsbeek & Nutman 1996); however, details of the contact relationships between the orthogneisses and supracrustal rocks were not reported, and the contact may be tectonic. Four zircons were also analysed from a rock interpreted in the field as a meta-andesite, which was collected from the apparent continuation of the Naternaq supracrustal belt 10 km to the east of the area shown in Fig. 1. One of the zircons gave an Archaean age, whereas the three others gave ages of 1900–2000 Ma that could either be metamorphic or protolith ages. Preliminary $^{207}Pb/^{206}Pb$ ages of around 2000 Ma recently obtained from detrital or volcanic zircons in a mica schist near 'Finger Lake' (Fig. 3; J.N. Connelly & K. Thrane, personal communication 2002) support the latter interpretation.

Naternaq supracrustal belt

The Naternaq supracrustal belt outlines a major, composite, overturned fold with an amplitude of about 25 km and straight limbs (Fig. 1). The thicker, south-eastern limb is up to *c.* 2 km wide, subvertical, and seems to extend *c.* 60 km towards the east-north-east; a large part is concealed by the Lersletten Quaternary deposits. The somewhat thinner north-western limb is *c.* 25 km long and has steep south-easterly dips. Axes of small-scale folds in the hinge zone, interpreted as representative for the orientation of the major fold, generally plunge moderately to steeply to the south-east. Steeply west-plunging folds are found within the south-eastern limb, which is commonly intensely folded internally. Outcrop patterns in different parts of the poorly exposed hinge zone suggest that the major fold structure is the result of more than one phase of folding, and refolded folds have been observed at a number of localities. It has, however, not been possible to establish a detailed deformation history. Intensely deformed horizons of supracrustal rocks with a northward concave flexure immediately to the west of the major fold may indicate the presence of a late NNE–SSW-trending (sinistral?) shear zone in this area.

Contacts between the supracrustal rocks and the regional tonalitic–granodioritic orthogneiss along the limbs of the major fold are generally sharp and intensely deformed, but the primary age relationships and nature of the contact are ambiguous. Variably deformed to almost undeformed masses of pink granite-pegmatite are particularly common in the hinge zone and postdate the orthogneiss. They are locally clearly discordant to the intensely deformed marginal part of the supracrustal belt and may have been emplaced during the development of the major overturned fold.

Three main rock types dominate the Naternaq supracrustal belt: amphibolite, fine-grained siliceous quartzo-feldspathic rocks, and garnet-mica schist. Quartzitic rocks, marble and calc-silicate rocks, carbonate and oxide facies iron-formation, and chert-rich layers interpreted as exhalites, are minor constituents. In spite of internal folding and possibly thrusting the supracrustal belt possesses a crude lithological stratigraphy which is interpreted as a primary feature. Amphibolite is consistently found along the outer margin of the major fold, succeeded towards the core by fine-grained siliceous quartzo-feldspathic rocks alternating with garnet-mica schist in which other horizons of amphibolite are intercalated. Where marble is present, mostly intercalated with calc-silicate rocks, it immediately succeeds the marginal amphibolite (Fig. 3).

Amphibolitic rocks

The amphibolites in most parts of the supracrustal belt are granoblastic to intensely schistose or lineated, mostly very fine-grained rocks primarily composed of hornblende and plagioclase, commonly with minor quartz and biotite, and locally garnet. Varieties with deformed, 1–5 cm long plagioclase aggregates (possibly former phenocrysts) have also been observed. In places medium-grained, homogeneous, plagioclase-rich 'grey amphibolite' and hornblende-quartz rocks occur. The main *c.* 200–400 m thick amphibolite unit at the margin of the belt commonly contains irregular, interconnected calc-silicate bands and lenses which are up to a few centimetres thick and more or less conformable with the main foliation; the adjacent amphibolite is commonly garnet-bearing. Locally, the calc-silicate rich layers are up to *c.* 20 cm thick and may be followed for tens of metres along strike. The fine-grained, calc-silicate banded amphibolites are interpreted as variably spilitised or hydrothermally altered, and subsequently strongly deformed, lavas and breccias. Small bodies of medium-grained, foliated to granoblastic, hornblende- or plagioclase-porphyroblastic varieties of probable intrusive origin also occur. Up to 10 m thick layers of biotite (-garnet) schist are common within the amphibolite. In the westernmost part of the hinge zone, as well as in other parts of the marginal amphibolite, 1–30 cm thick layers of very fine-grained siliceous, muscovite- and biotite-bearing, pale grey metasedimentary or metavolcanic rocks are interleaved with the amphibolite.

Chemical sedimentary rocks, banded iron-formation and sulphide mineralisation

In the southern and north-western parts of the supracrustal belt, especially near the lakes designated 'Round Lake' and 'Finger Lake' by KØ (Fig. 3), the marginal amphibolite is succeeded by an irregular, and in most places intensely deformed sequence of chemical sediments. These mainly consist of marble, with minor carbonate and oxide facies banded iron-formation and cherty exhalites, the latter locally with semi-massive to massive sulphide mineralisation (see below). The detailed map of this area (Fig. 3) shows up to three separate sequences of marble and exhalites with sulphide mineralisation, which is due to repetition of a single original sequence by folding.

The scattered, up to *c.* 100 m thick marble occurrences near 'Round Lake' and 'Finger Lake' (Fig. 4) mainly consist of impure, greyish to brownish weathering, fine-grained dolomitic marble, commonly with centimetre- to decimetre-thick intercalations of calcite marble and calc-silicate rocks dominated by tremolite-actinolite + diopside ± dolomite and late talc. The lack of forsterite and the presence of sillimanite in adjacent pelitic rocks suggest P–T conditions of approximately 650 ± 50°C at

Fig. 4. Dolomitic marble in the southern part of the Naternaq supracrustal belt (location shown on Fig. 3).

Fig. 5. Carbonate-oxide facies banded iron-formation in the southern part of the Naternaq supracrustal belt (location shown on Fig. 3). Hammer: 50 cm.

Fig. 6. Weathered-out chert-sulphide concretions of possible diagenetic origin in sulphide-mineralised host in the southern part of the Naternaq supracrustal belt (location shown on Fig. 3). Hammer: 50 cm.

4.5 ± 0.5 kbar; tremolite-actinolite may have grown during decreasing temperature. A few other marble horizons up to about two metres thick have also been found at approximately the same stratigraphic level, e.g. in the hinge zone of the major fold. The banded iron-formation forms sporadic, 0.5–1 m thick layers on the south-eastern fold flank along strike of the dolomite marble, and consists of alternating centimetre-thick layers of dolomite, magnetite, siderite, quartz and calc-silicate minerals. A single, larger, *c.* 30 × 40 m fold closure with the same type of banded iron-formation crops out east-north-east of 'Finger Lake' (Fig. 5).

A range of variably altered, conformable horizons of very fine-grained siliceous and sulphidic lithologies associated with either amphibolite or marble are interpreted as volcanogenic-exhalitic rocks. Light grey, finely laminated (millimetre-scale) cherty rocks predominate and usually contain up to *c.* 20% dark, very fine-grained sulphidic seams. The fine lamination, which may be a primary feature, is in most places destroyed by intense secondary alteration characterised in the field by a sulphide-yellow, variably rusty appearance. Seams of fine-grained dolomite and micaceous metasediments are commonly intercalated with the mineralised cherty layers, resulting in composite, rusty weathering outcrops with variable mineralogy.

The largest semi-massive to massive pyrrhotite-rich sulphide mineralised zones are found near 'Round Lake' and 'Finger Lake' (Fig. 3). Massive sulphides form up to *c.* 2 m wide and 10 m long lenses (maximum size 2 × 10 m); the mineralised rocks are iron-rich and dominated by pyrrhotite, with minor chalcopyrite and sphalerite (up to *c.* 3%) and subordinate pyrite, arsenopyrite, magnetite

Fig. 7. Sulphide mineralisation concentrated in the hinge areas of metre-scale angular folds. Southern part of the Naternaq supracrustal belt (location shown on Fig. 3). Hammer: 50 cm.

and graphite. Thinner, conformable horizons containing disseminated to semi-massive sulphides may be followed for up to a few hundred metres. Within one of the mineralised zones at 'Finger Lake', a number of 10–40 cm chert-sulphide concretions were observed in a pyrrhotite-rich, semi-massive sulphidic host rock (Fig. 6). It is considered likely that these concretions were formed during the mineralising event itself, or the subsequent diagenesis. Disseminated sulphides are common in the host amphibolite, marble and mica schist adjacent to the massive and semi-massive sulphide occurrences.

Metre-sized and larger, tight, overturned, angular folds are common in the mineralised areas. Many of the massive sulphide lenses occur in the hinge zones of such small-scale folds (Fig. 7), indicating a certain degree of hydrothermal sulphide remobilisation during the pervasive ductile deformation. However, detailed mapping south-east of both 'Round Lake' and 'Finger Lake' shows that these lenses could be stratigraphically connected with each other. The sulphidic, exhalite horizons are commonly extensively crushed along narrow, secondary fault zones.

Quartzitic rocks

Discrete, 1–5 m thick, fine-grained quartzitic horizons *s.s.* with thin magnetite-rich seams, presumably of clastic sedimentary origin, are found locally adjacent to the marble. Another quartzitic unit without magnetite seams, but containing dispersed, fine-grained biotite, occurs on the south-eastern limb of the major fold some 15 km east of the area shown in Fig. 3. It has a strike length of *c.* 2 km and is up to 30–40 m thick.

Fine-grained siliceous and pelitic metasediments

The interior part of the supracrustal belt at Naternaq with respect to the major overturned fold is a *c.* 200–300 m thick succession of mainly siliceous, muscovite schists together with minor biotite-garnet schists and amphibolite. The siliceous schists are generally light grey to light brown in colour and very fine-grained; they commonly have a very massive appearance without much apparent lithological variation, and no primary structures have been observed. In some places they contain up to centimetre-sized porphyroblasts or pseudomorphs of andalusite. Garnet-rich horizons are common adjacent to amphibolite contacts. The origin of the siliceous schists is not clear from their field appearance alone; they may be metasedimentary or metavolcanic rocks, or a mixture of both (see discussion).

Garnet-mica schists, commonly sillimanite-bearing, generally fine- to medium-grained and with a strong penetrative S fabric, are intercalated with the siliceous schist and fine-grained amphibolite in layers from a few centimetres to tens of metres thick. In some areas the schists contain irregular to strongly planar quartzo-feldspathic melt veins on a centimetre-scale, which give them a migmatitic appearance.

Supracrustal rocks of the Ikamiut district

Supracrustal rocks crop out extensively south and west of Ikamiut, the settlement between the bays of Nivaap Paa and Sydostbugten in the south-east corner of Disko

Bugt (Fig. 1; Henderson 1969). The area was mapped in some detail in August 2001, allowing refinement and simplification of Henderson's original map and resolving some of the peculiarities of outcrop pattern that arose from his reconnaissance mapping. The supracrustal rocks are dominated by siliciclastic rocks, with subordinate but important amphibolite horizons.

Relationships between orthogneisses and supracrustal rocks

The supracrustal rocks are interlayered with granodioritic to tonalitic orthogneisses. As far as could be determined, the interlayering is tectonic. Where contacts between supracrustal rocks and orthogneisses can be observed unambiguously, they are generally marked by high strain and extensive mylonitic developments.

On the west coast of Naajannguit, 5.7 km due west of Ikamiut in the northern part of the area (Fig. 1), a unit of supracrustal rocks is sandwiched between orthogneisses. The contacts on both sides of this supracrustal unit are highly strained and marked by mylonites, indicating tectonic interleaving. The orthogneisses seen here seem to contain an additional phase of deformation to that affecting both the orthogneisses and the supracrustal rocks as a whole.

Relationships between the orthogneisses and supracrustal rocks are somewhat obscure in the central part of the Naajannguit area, where distinction between siliceous and psammitic supracrustal lithologies and orthogneisses is rendered difficult by similarities in composition and partial melting effects. No cross-cutting relationships that would indicate an intrusive relationship have been observed, but such relationships may have been obscured by the deformation. Such extremely limited evidence as there is suggests that the supracrustal rocks were deposited upon the orthogneisses, but this remains to be confirmed. The orthogneisses and metasedimentary rocks are disposed about kilometre-scale open to tight upright folds that fold the penetrative fabric in the rocks as well as the mylonitic contacts between the orthogneisses and the metasedimentary rocks. A strong, penetrative stretching lineation is consistently parallel to the WSW-plunge of the major folds.

Supracrustal lithologies

The dominant supracrustal lithologies are psammites, micaceous psammites, schistose to gneissose pelites and semipelites. Siliceous psammitic and quartzitic lithologies are also present, and amphibolites form a subordinate but important component. No unambiguous evidence of younging was found, although possible graded bedding was observed at one locality, suggesting the rocks are the right way up.

The semipelitic and pelitic lithologies are well exposed on the north-western side of Puagiarsuup Ilua. They are coarse, schistose to gneissose migmatitic rocks with ubiquitous thin, centimetre-scale, lenticular quartz-feldspar leucosome veins, commonly with biotite-rich selvages. Garnet is commonly abundant and is wrapped by the penetrative schistose to gneissose fabric. Sillimanite is present locally and, in one or two places, appears to be a pseudomorph after kyanite. Sillimanite is also seen replacing biotite. Locally, coarse quartz-plagioclase pegmatite is abundant, forming metre-thick, lenticular bodies within the micaceous host rock. Local garnet, muscovite and sillimanite in the pegmatites indicate derivation from a metasedimentary source. Other 'pegmatitic' bodies of pale rock in this area are layered internally and may be deformed psammites within the more pelitic rocks.

The psammitic rocks vary from medium- to coarse-grained, dark, micaceous psammites to pale, quartzitic rocks. Contacts with the semipelitic–pelitic lithologies are transitional to sharp. The psammitic rocks are locally garnet-bearing and, where amphibolites occur in adjacent outcrops, may also contain amphibole, suggesting a volcanic input. The more micaceous psammitic rocks are commonly migmatitic, with a quartz-feldspar leucosome. While all the siliceous rocks are likely to be sedimentary in origin, it is possible that some of them may have been acid volcanic rocks.

Although subordinate in volume, there are significant units of amphibolite, some of which contain abundant large garnet porphyroblasts with very fine-grained quartz-plagioclase pressure shadows. The amphibolites are locally massive, but tend generally to be layered and heterogeneous, with diopsidic and plagioclase-rich layers and marginal developments of thinly layered, calc-silicate-bearing units. The amphibolite units are lenticular and of limited lateral extent. A particularly fine sequence of layered calc-silicate-bearing rocks crops out on the peninsula north-west of Ikamiut, where they are characterised by the presence of diopside with some dark brown orthopyroxene. From their lithological character, it is considered that the amphibolites and associated rocks are most likely to be metavolcanic in origin. Sulphide mineralisation occurs locally at the margins of amphibolites, where calc-silicate-bearing units are developed.

Regional correlation

The Ikamiut supracrustal rocks are, in general, very similar to those described from Naternaq, although no carbonate rocks, marbles, banded iron-formation or layered cherts have been recorded in the Ikamiut area. Thus the Ikamiut rocks are provisionally correlated with those from Naternaq, with a possible continuation to the north-east along strike from Ikamiut.

Discussion and conclusions

An interpretation of the depositional age and plate-tectonic setting of the Naternaq supracrustal belt is essential for an evaluation of its economic potential. However, the available geochronological data are not sufficient to confidently determine its age. While observations from adjacent areas in 2001 indicate that the orthogneiss precursors are likely to have been intruded into supracrustal packages (van Gool *et al.* 2002, this volume), in the Ikamiut area there are hints of a depositional unconformity.

Age determinations of orthogneisses farther south in the Nagssugtoqidian orogen have shown that almost all are Archaean. The only exception is the *c.* 1900 Ma Arfersiorfik quartz diorite, which was emplaced between the two Archaean continents that collided during the Nagssugtoqidian orogeny and was involved in the ensuing thrust stacking of Archaean and Palaeoproterozoic crust in the central part of the orogen (e.g. Kalsbeek *et al.* 1984, 1987; Connelly *et al.* 2000). Field observations in 2001 by one of the authors (A.A.G.) suggest that the northern limit of the thrust stack straddles 68°N. A preliminary conjecture based on the structural and geochronological data currently available indicates that the orthogneisses in the Naternaq area belong to the northern continent and are late Archaean in age, that large fold structures farther to the south-west and hence also the supracrustal rocks in that area are Archaean, but that the Naternaq supracrustal belt and its fold structures are Palaeoproterozoic.

Due to ubiquitous high strain along the contacts between the Naternaq supracrustal belt and the orthogneisses it is not known with certainty whether the former were deposited on the latter with a primary depositional unconformity, or whether the two units are tectonically interleaved. A third possibility, that the gneiss precursors intruded the supracrustal sequence, seems less likely in view of the recent age determinations of zircons from the supracrustal belt reported above. This unresolved problem has an important bearing on the evaluation of the economic potential of the supracrustal belt: is this a predominantly clastic epicontinental sequence with a low economic potential, or is it an arc-related, predominantly volcanic, bimodal sequence comprising a lower, basic sequence (the marginal amphibolite) and an upper, acid sequence (the siliceous mica schists), and thus with an interesting base metal and gold potential? Further study of the siliceous mica schists, including geochemistry and more precise age determinations of their zircons, may provide an answer to this question. In addition, future work may show that both Archaean and Palaeoproterozoic supracrustal rock sequences occur side by side in the Naternaq area.

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Authors' addresses

C.Ø., *Aggersvoldvej 15, 2. tv., DK-2700 Brønshøj, Denmark.* E-mail: *thin.air@get2net.dk*

A.A.G., B.M.N. & H.S., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.*

J.N., *Jægersborggade 2, 1. th., DK-2200 Copenhagen N, Denmark.*

J.B., *Bureau of Minerals and Petroleum, Government of Greenland, P.O. Box 930, DK-3900 Nuuk, Greenland.*

C.W.T., *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK.*

A coastal survey in the southern part of the Palaeoproterozoic Rinkian fold belt, central West Greenland

Adam A. Garde, James N. Connelly, Adam W. Krawiec, Sandra Piazolo and Kristine Thrane

A brief but potentially important part of the 2001 field investigations in the Precambrian of West Greenland (van Gool *et al.* 2002, this volume) was devoted to the southernmost part of the Palaeoproterozoic Rinkian fold belt east of Disko Bugt (Fig. 1). From 9–17 August the five authors carried out a reappraisal of critical Archaean and Proterozoic relationships and collected samples for precise geochronological studies. The principal aims are to date the main Rinkian tectonic and metamorphic events in this region as precisely as possible and compare them with the evolution of the Nagssugtoqidian orogen to the south (see van Gool *et al.* 2002, this volume, fig. 1). The vessel M/S *Søkongen* provided logistic support; a helicopter provided transport to Nunatarsuaq.

Geological background

The Archaean continental terrains in West and East Greenland, north-eastern Canada, Scotland and Scandinavia were gradually amalgamated during a series of major Palaeoproterozoic orogenic events to form one of the earliest large continents on Earth. Recent structural and geochronological studies have significantly improved the correlation between the individual orogens and the understanding of the overall plate-tectonic framework (e.g. Clowes *et al.* 1999), but there remain significant geographical, chronological and structural uncertainties. One of these concerns the boundary zone between the Nagssugtoqidian and Rinkian orogenic belts in central West Greenland (van Gool *et al.* 2002, this volume, fig. 1). It is quite possible that the two belts formed contemporaneously within a common, or at least related, plate-tectonic setting. However, the structural styles of the two belts are different; at least one part of the contact region between the two belts only displays very weak Palaeoproterozoic reworking, and only a rudimentary geochronological data base is currently available for the Rinkian belt.

Recent geochronological and structural studies in the southern and central Nagssugtoqidian orogen by the Danish Lithosphere Centre have established an accurate and robust time-frame for the accretion of its Archaean magmatic elements, the Palaeoproterozoic magmatic arc component, its subsequent tectonic accretion, and final stabilisation (Connelly *et al.* 2000; Willigers *et al.* 2002). These insights are being largely corroborated by ongoing work in the northern Nagssugtoqidian orogen (van Gool *et al.* 2002, this volume).

Such constraints are not yet available for the Rinkian fold belt (Henderson & Pulvertaft 1987; Grocott & Pulvertaft 1990; Kalsbeek *et al.* 1998). During the most recent investigations by the Survey conducted in 1988–1991 (Kalsbeek 1999), it was established that Rinkian structural reworking was strong in eastern Nuussuaq, southern Arveprinsen Ejland and areas to the east. In contrast, the intervening Ataa domain was largely unaffected by reworking (Fig. 1; Kalsbeek *et al.* 1988; Escher *et al.* 1999; Garde & Steenfelt 1999a, b; Grocott & Davies 1999). An Ar-Ar and K-Ar geochronological study confirmed this general interpretation but with a broad spread of ages (Rasmussen & Holm 1999). A few ion probe U-Pb zircon ages, whole-rock Pb-Pb and Rb-Sr ages and model Sm-Nd ages showed that both the Atâ tonalite and adjacent supracrustal lithologies in the Ataa domain were magmatically accreted at 2800 Ma (Kalsbeek & Taylor 1999; Nutman & Kalsbeek 1999). However, the age histories of the reworked, supposedly Archaean basement of Nuussuaq and the Palaeoproterozoic reworking north and south of the Ataa domain have yet to be unravelled.

In this contribution, we present a summary of our main objectives in the southern part of the Rinkian fold belt and relate them to the geological problems outlined above. An overview of the southern part of the Rinkian belt can be found in Garde & Steenfelt (1999a).

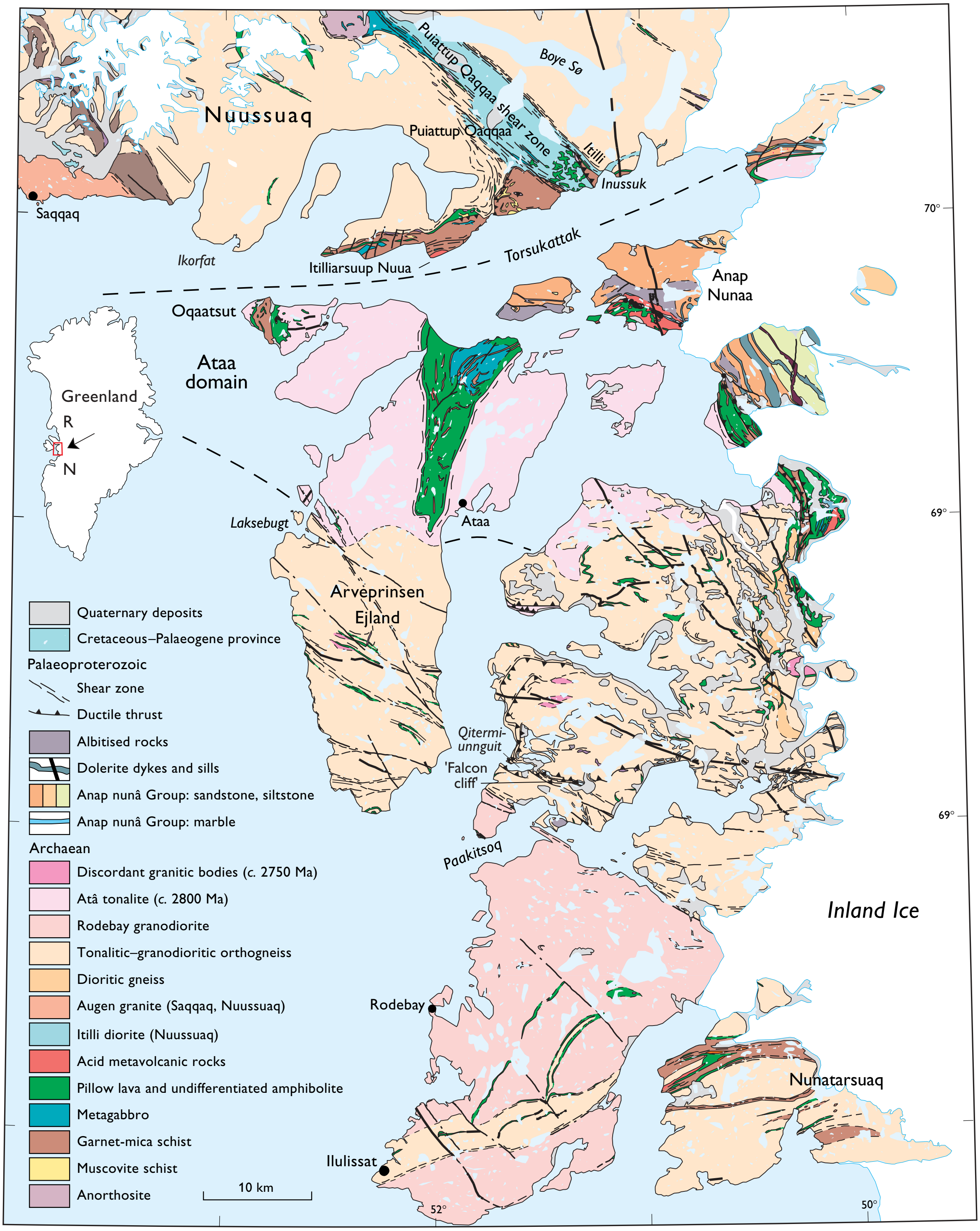

Fig. 1. Geological sketch map of the area north-east of Disko Bugt with place names used in the text, modified from Garde (1994). **Dash lines**: domain boundaries. **Filled circles**: towns, settlements. **Open circle**: abandoned settlement. **Dash-dot lines**: faults. **N** and **R** on the inset map of Greenland denote the Nagssugtoqidian and Rinkian belts, with the map area at the **arrow** (also shown on van Gool *et al*. 2002, this volume, fig. 1).

Archaean acid metavolcanic rocks and the Torsukattak shear zone, south coast of Nuussuaq

The Survey's field work in Nuussuaq in 1988–1991 was largely restricted to helicopter reconnaissance; due to difficult ice conditions and lack of a suitably large boat, the south coast was not mapped. Nevertheless, a preliminary lithostratigraphy of the main, supposedly Archaean supracrustal sequences in southern Nuussuaq was established (Garde & Steenfelt 1999a), and two major Proterozoic shear zones were proposed: (1) the well-exposed, NW–SE-trending *Puiattup Qaqqaa shear zone* in southern Nuussuaq, and (2) the *Torsukattak shear zone*, a largely unexposed younger extensional shear zone along the fjord Torsukattak with oblique downthrow to the south-east (Fig. 1). The existence of the latter shear zone was mainly inferred from numerous inland observations of intense SE-plunging extension lineations, apparent tectonic reworking of the Puiattup Qaqqaa shear zone towards Torsukattak, and an abrupt decrease in the overall metamorphic grade between southern Nuussuaq and the Ataa domain (for details see Garde & Steenfelt 1999b).

In 2001, it was possible to study the outcrops along the coast of Nuussuaq by boat in spite of much ice (Fig. 2). An acid metavolcanic rock with pale, fine-grained volcanic clasts (Fig. 3) from a previously reported supracrustal sequence north of Itilliarsuup Nuua (Fig. 1; Garde 1994) was sampled in order to obtain a depositional age for the metavolcanic rock by U-Pb dating of its igneous zircons (using the conventional thermal ionisation method, TIMS); this will also provide a minimum age for the underlying Nuussuaq gneisses, and will allow us to compare the timing of volcanism at the continental margin of southern Nuusuaq with the arc-type volcanism in the Ataa domain, which was previously dated at *c.* 2800 Ma (Kalsbeek & Taylor 1999). In addition, the zircon U-Pb system might also provide a discordia age for the Torsukattak shear zone.

During a boat traverse of the excellently exposed, SSE-dipping acid metavolcanic and associated metasedimentary rocks we observed asymmetric volcanic clasts and garnet porphyroclasts within the intense, SE-plunging LS fabric. The asymmetric fabric elements clearly indicate relative downthrow of the southern hanging wall towards the south-east along the steep lineation (Fig. 4), corroborating Garde & Steenfelt's (1999b) interpretation that the Torsukattak structure is a major, oblique extensional shear zone. It was previously noted in inland areas that the intensity of the LS strain fabric

Fig 2. M/S *Søkongen* in the ice-filled waters of Torsukattak, north-west of Anap Nunaa.

Fig. 3. Fragmental acid metavolcanic rocks at Itilliarsuup Nuua. Pencil for scale.

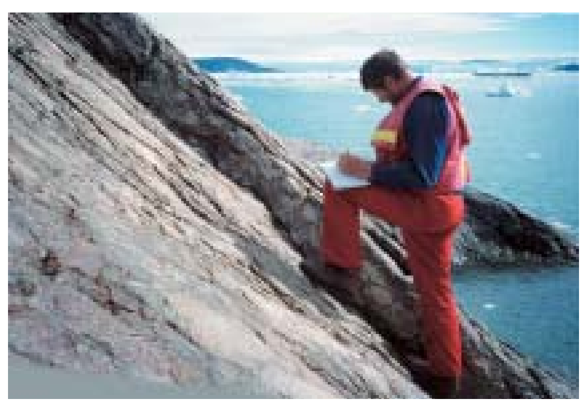

Fig. 4. Asymmetric fabric elements (volcanic clasts) at Ililliarsuup Nuua, indicating relative downthrow of the southern (right-hand) side of the Torsukattak shear zone. View eastwards along the south coast of Nuussuaq.

increases towards the south. We observed that the strain intensity reaches a maximum about 50 m from the point of Itilliarsuup Nuua, where ultramylonitic rocks occur. Further south, towards the point itself, the intensity of the LS fabric decreases significantly. It is concluded that the central part of the Torsukattak shear zone is probably not hidden in the fjord as hitherto believed, but may be located close to Itilliarsuup Nuua.

Other supracrustal rocks of supposed Archaean and Palaeoproterozoic age

Garnet- and biotite-rich metasedimentary rocks at Inussuk near the head of Torsukattak, Oqaatsut and on Nunatarsuaq were sampled for U-Pb ion probe studies of detrital zircons and microtextural and metamorphic studies. In addition, dating of metamorphic minerals may allow determination of the cooling path (U-Pb: titanite, apatite; Rb-Sr: biotite, muscovite). Samples of low-grade sedimentary rocks from the Anap nunâ Group were also collected on northern and south-eastern Anap Nunaa.

Archaean basement of southern Nuussuaq and in the Ilulissat/Jakobshavn area

Representative samples of orthogneiss and granitic rocks were collected from various parts of the Archaean basement in the southern Rinkian belt and the border region to the Nagssugtoqidian orogen as part of an ongoing regional age characterisation of the Archaean basement in West Greenland. The sampled units include grey tonalitic orthogneiss and associated younger granitoid phases at the embayment 2 km west of Ikorfat, granodioritic augen gneiss *c.* 5 km west of Saqqaq, Itilli diorite north of inner Torsukattak, grey tonalitic orthogneiss at western Arveprinsen Ejland at Laksebugt, Ilulissat harbour and Ilulissat airport, and Rodebay granite at Rodebay (Fig. 1).

North- to west-directed Proterozoic thrusting of Archaean orthogneisses at Paakitsoq

In the area south of the Ataa domain, which was affected by significant Palaeoproterozoic reworking, Escher *et al.* (1999) reported major low-angle ductile imbrication of Archaean orthogneisses in the vicinity of Paakitsoq. The main thrusting is envisaged to have occurred during an early phase of Proterozoic deformation, and according to Escher *et al.* (1999) the predominant movement direction of the thrusts was westwards. The thrusting event was followed by open to tight folding, and the thrusts were reactivated during the emplacement of a suite of up to *c.* 100 m thick mafic sills. These were commonly emplaced along thrust planes and were subsequently boudinaged and their margins deformed during continued movement along the thrusts (Escher *et al.* 1999, table 1). The sills and their host rocks are cut by dolerite dykes as well as thin lamprophyre dykes and sills; the latter were dated at *c.* 1750 Ma by Larsen & Rex (1992).

Fig. 5. Mylonitised orthogneiss with asymmetric porphyroclasts and extension lineation, north coast of Qitermiunnguit.

It is of critical importance for the correlation between the Rinkian and Nagssugtoqidian belts that a comparison can be made between the timing of the Rinkian west-directed thrusting and the main crustal shortening event in the central Nagssugtoqidian orogen at *c.* 1860–1820 Ma (Connelly *et al.* 2000). Therefore, it is important to determine as precisely as possible when the main episode of thrusting at Paakitsoq prior to the sill emplacement took place. Our attention was focused on the orthogneisses at Qitermiunnguit and on the coast of north-eastern Paakitsoq (Fig. 1) which are readily accessible and in structural continuation with those at the 'Falcon cliff' of Escher *et al.* (1999, fig. 8). At both localities subhorizontal, upper greenschist to lower amphibolite facies high-strain zones up to a few metres thick, which are commonly ultramylonitic, are separated by up to *c*. 100 m thick zones of much less deformed rocks. In the high-strain zones there are abundant, well-developed, asymmetric δ- and σ-shaped K-feldspar and plagioclase porphyroclasts within the LS fabric (Fig. 5), which is dominated by an intense, shallowly east-plunging extension lineation. It was easy to confirm the main westerly transport direction previously reported from other localities, e.g. at 'Falcon cliff'. Several orthogneiss samples were collected for U-Pb zircon geochronology: we hope to date the intense ductile deformation by means of precise lower concordia intercepts.

The *c.* 1650 Ma Melville Bugt dyke swarm at inner Torsukattak

In order to close the present gap in the existing data set of palaeomagnetic poles used to constrain Palaeoproterozoic to Mesoproterozoic plate reconstructions of Laurentia and Baltica (Buchan *et al.* 2000, 2001), a *c.* 100 m wide dyke belonging to the Melville Bugt dyke swarm of North-West Greenland and its contact rocks were sampled in inner Torsukattak. This particular dyke has a strike length of 400 km and was previously studied by Kalsbeek & Taylor (1986), who obtained a Rb-Sr age of 1645 ± 35 Ma. In addition to a sample set for the palaeomagnetic studies, a very large sample was collected from the dyke centre in the hope of retrieving magmatic zircon or badelleyite for precise dating.

Concluding remarks

The survey north-east of Disko Bugt initiated in 2001 is a geochronological, structural and metamorphic study that aims to update understanding of the Rinkian orogen and its position in the contemporaneous framework of Palaeoproterozoic orogens in Greenland and eastern Canada. In 2002, with support from the Carlsberg Foundation, the survey will be extended into the central part of the Rinkian fold belt.

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Authors' addresses

A.A.G., S.P. & K.T., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* E-mail: *aag@geus.dk*

J.N.C. & A.W.K., *Department of Geological Sciences, University of Texas at Austin, Austin, TX 78712, USA.*

The mineral resource potential of the Nordre Strømfjord – Qasigiannguit region, southern and central West Greenland

Henrik Stendal, Jette Blomsterberg, Sven Monrad Jensen, Mogens Lind, Heine Buus Madsen, Bo Møller Nielsen, Leif Thorning and Claus Østergaard

Assessment of the mineral resource potential of the region between Sukkertoppen Iskappe and the southern part of Nuussuaq, West Greenland (66°N to 70°15´N; Fig. 1) is part of a regional resource assessment programme of the Geological Survey of Denmark and Greenland (GEUS) for 2000–2003. The year 2000 was dedicated to the compilation of existing data and the outlining of target areas for the field work in 2001 and 2002. This report gives a review of the work related to the gold and base metal potential in the Nordre Strømfjord – Qasigiannguit region, mainly based on results from the 2001 field work.

Significant geological data have been collected from the region by the Survey, research groups and exploration companies during the past several decades; see Kalsbeek & Nutman (1996), Connelly & Mengel (2000) and van Gool *et al.* (2002, this volume) for geology, Steenfelt (2001) for geochemistry and Rasmussen & van Gool (2000) and Nielsen & Rasmussen (2002, this volume) for geophysics. Most of the region is easy of access, and exposures are excellent along the shores of the numerous fjords. However, inland areas may locally have extensive Quaternary cover.

The target areas (Fig. 2) for the search for mineral occurrences in 2001 were chosen on the basis of compilations of all types of existing data, including the *Ujarassiorit* ('public mineral hunt') programme (e.g. Roos 1998).

Previous exploration

Exploration companies have been active in different parts of the region since 1960. Kryolitselskabet Øresund A/S conducted mineral exploration and prospecting from the early 1960s until the late 1970s, with particular emphasis on investigations of rust zones (Keto 1963; Vaasjoki 1964, 1965; Kurki 1965a, b; Gothenborg 1980; Gothenborg & Keto 1980). During the geological mapping for the Survey's 1:100 000 Agto (= Attu) map sheet between 1965 and 1978, discontinuous, stratiform massive iron sulphide mineralisations were found in supracrustal rocks around the fjord Ataneq (Fig. 2; Platou 1967). Nunaoil A/S prospecting in the Agto map sheet area during the early 1990s included helicopter-based regional heavy mineral concentrate and stream sediment sampling that was followed up in selected areas by further investigations (Geyti & Pedersen 1991; Gowen 1992; Sieborg 1992; Grahl-Madsen 1993, 1994). The main target of their investigations was location of base and noble metal deposits in exhalative settings. Later in the 1990s, RTZ Mining and Exploration Ltd (Coppard 1995) and Inco Ltd (Car 1997) prospected for Ni-Cu and PGM deposits, inspired by the spectacular discoveries in rocks of comparable age at Voisey's Bay, Labrador (Li & Naldrett 1999).

Geological setting

The study region comprises parts of the Palaeoproterozoic Rinkian mobile belt and Nagssugtoqidian orogenic belt (van Gool *et al.* 2002, this volume). The 2001 investigations were concentrated in the northern Nagssugtoqidian orogen (NNO), which consists dominantly of Archaean orthogneisses and paragneisses with several thin belts of supracrustal and intrusive rocks. Granitic rocks and numerous pegmatites intrude the gneisses. Palaeoproterozoic rock units are limited to the Arfersiorfik intrusive suite and minor supracrustal sequences (Connelly & Mengel 2000).

Metamorphic grade is mainly amphibolite facies; the southern part of the NNO south of Ataneq (Fig. 1) is in granulite facies, as is most of the central Nagssugtoqidian orogen (CNO). The gneisses are intensely folded and exhibit general E–W and NE–SW trends. The Palaeoproterozoic reworking of the Archaean gneisses in the NNO decreases gradually northwards,

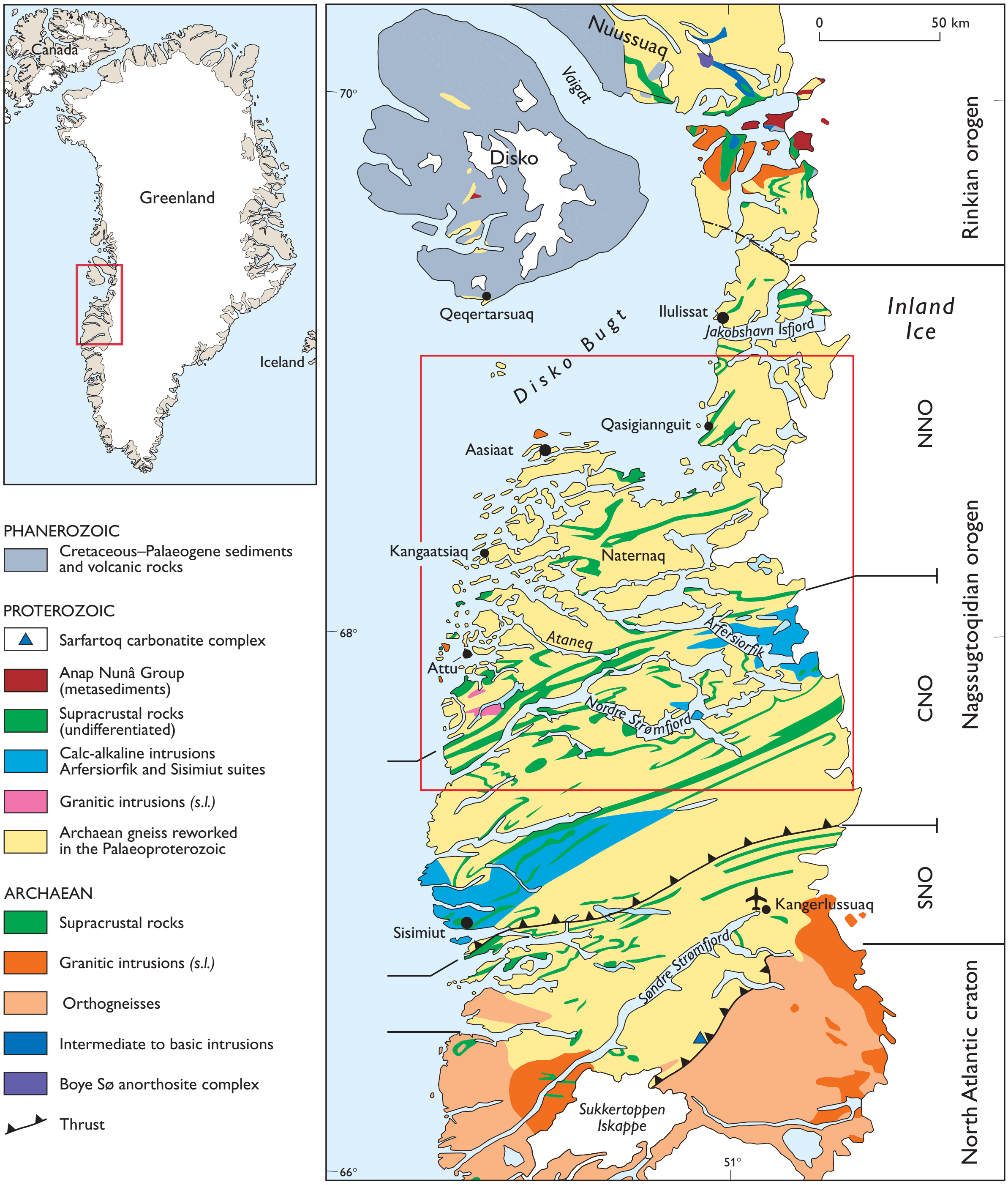

Fig. 1. Geological map of the assessment region in West Greenland. **Red frame** delineates the 2001 field study region. **SNO**, **CNO** and **NNO** are, respectively, the southern, central and northern Nagssugtoqidian orogen. Slightly modified from van Gool *et al.* (2002, this volume).

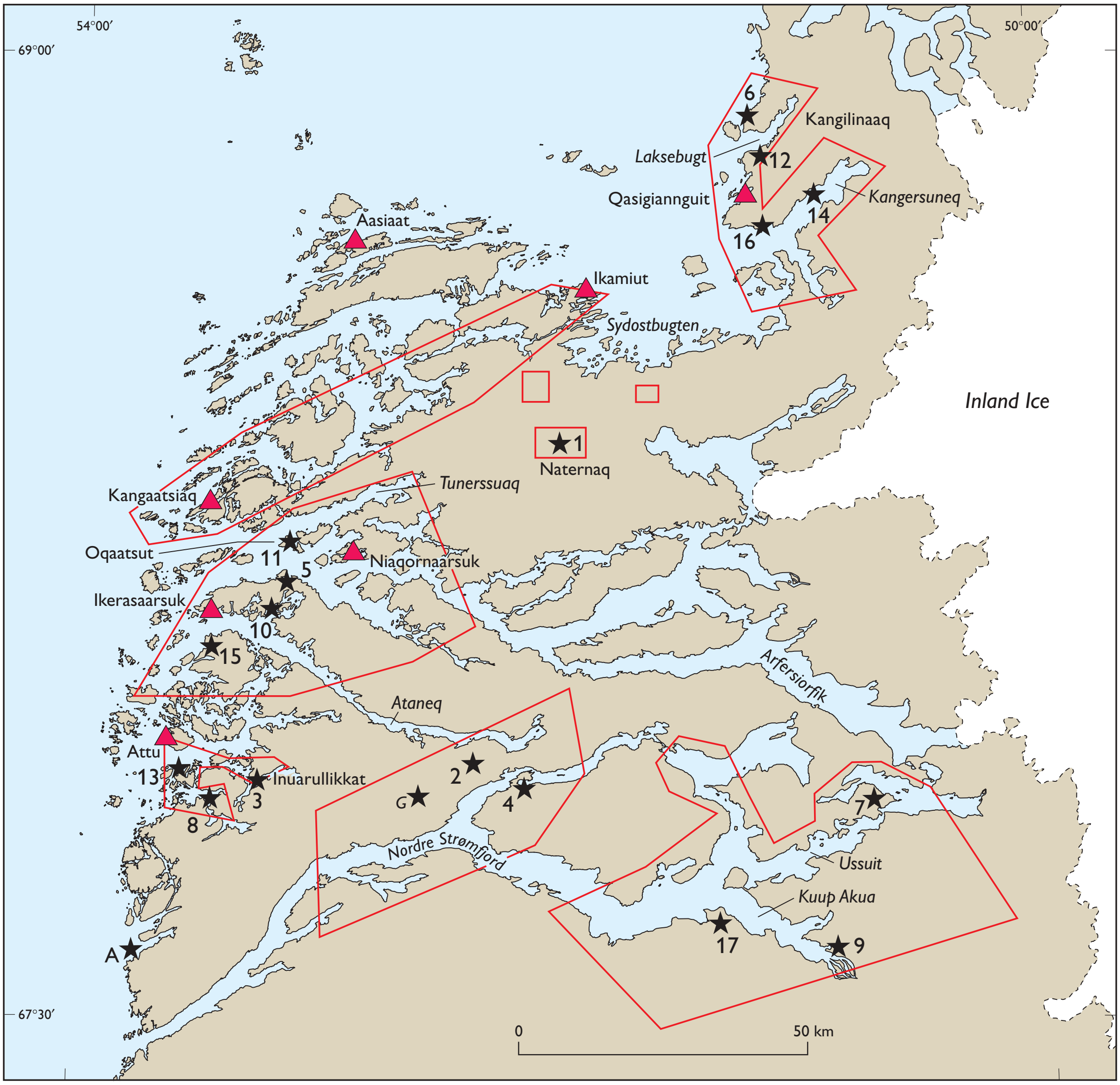

Fig. 2. Index map of the 2001 study region. The **framed areas** are where the main 2001 field work was carried out. **Numbers** refer to the described localities in the text. **A**: Akuliaruseq; **G**: Giesecke Sø.

e.g. from high strain in the south to a more open style of deformation in the north. Steep- and shallow-dipping shear and fault zones are common in contact zones between different types of lithologies. Major fault zones generally trend between NNE–SSW and NE–SW.

The gneisses of the NNO have yielded late Archaean ages between 2870 and 2700 Ma (Kalsbeek & Nutman 1996; Connelly & Mengel 2000), and a discordant Archaean granite occurs in the central part of the NNO (Kalsbeek & Nutman 1996). Only a few younger Palaeoproterozoic ages have been recorded, including an age of about 1790 Ma from an undeformed pegmatite between Attu and Aasiaat (Connelly & Mengel 2000).

Mineral occurrences

Most of the mineral occurrences in the region are small and their economic potential is limited; at present, the largest known occurrence is the Naternaq pyrrhotite deposit. Descriptions of the different types of mineral occurrences are given below, where the reference numbers refer to localities in Fig. 2.

Naternaq massive sulphides

The Naternaq supracrustal belt consists of metavolcanic rocks interlayered with pelitic and psammitic metasediments, carbonate/marble units, exhalites and/or chert-rich layers, and minor quartzite and banded iron-formation. In total, these units make up an up to 3 km thick supracrustal sequence which is folded into a major shallow-dipping ENE–WSW-trending antiform; the supracrustal sequence can be traced for approximately 30 km along strike, around the nose of the antiform and into the northern limb. Massive granite sheets and pegmatite veins intrude the supracrustal rocks in the central part of the belt. A detailed description of the stratigraphy of the supracrustal rocks is given by Østergaard *et al.* 2002 (this volume).

Massive to semi-massive sulphide occurrences are found in several distinct rusty beds within the Naternaq supracrustal belt (**1**; Fig. 2), which occur close to the contact of a fine-grained metavolcanic amphibolite with a discontinuous carbonate unit. The mineralised beds consist of banded chert layers, 'black ore' sediments and calcareous schists, and are found both within the amphibolite and the adjacent calc-silicate developments (Fig. 3). Banded iron-formation occurs locally in the amphibolite as exhalite zones composed of cm-banded layers of magnetite, siderite ± quartz and calc-silicates.

Massive sulphide lenses (70–90 vol.%) are usually 2 × 4 m in size, but lenses up to 2 × 10 m across have been observed. Semi-massive sulphides (20–50 vol.%) occur as 0.5–1 m thick parallel zones that can be followed for 50–100 m along strike. The Fe-sulphide content is generally high. The occurrences are characterised by pyrrhotite with minor chalcopyrite and sphalerite, together with subordinate pyrite, arsenopyrite, magnetite and graphite. The sulphide ore may occur within the core of folds, as a result of remobilisation by hydrothermal/metamorphic fluids. Chemical analyses have yielded up to 2.7% Cu and 3.75% Zn, with gold values of 20–80 ppb (Vaasjoki 1965). The sulphide concentrations were estimated by Vaasjoki (1964) to amount to 2.4–4.8 million tonnes of indicated resource and 8.1–16.2 million tonnes of inferred resource.

Nordre Strømfjord pyrrhotite

Between Giesecke Sø (Fig. 2) and Ataneq, semi-massive pyrrhotite lenses can be traced over a strike length of about 22 km (2; Fig. 2). The lenses occur in two parallel layers up to one metre thick and with varying length (10–100 m) within a supracrustal sequence composed of foliated amphibolite and biotite-garnet (± graphite ± sillimanite) paragneisses. The supracrustal rocks have a general strike of 265° and dip 60°N, parallel to the Nordre Strømfjord shear zone (van Gool *et al.* 2002, this volume). The most common host rocks to the pyrrhotite lenses are skarn, amphibolite, biotite-garnet gneiss and altered silicified lithologies, occasionally with conspicuous amounts of graphite. Chip samples of the mineralised pyrrhotite beds yield up to 0.3% Cu, 4% Mn, 600 ppm Ni and 400 ppm Zn.

Fig. 3. Naternaq massive sulphide deposit ('Rust Hill') with the characteristic yellow-brown weathering colour (locality 1 in Fig. 2). Distance across the hill is *c.* 100 m.

Iron-formation at Inuarullikkat

At the fjord Inuarullikkat a well-exposed, 10–20 m wide magnetite-bearing amphibolite occurs intercalated with brown coloured gneisses (3; Fig. 2) and can be followed continuously along the coast for several kilometres. The magnetite-bearing layer (Fig. 4) is a 1.5 m thick banded iron-formation with a NE–SW strike and 54° dip to the north-west, and comprises alternating 1–10 mm wide bands of magnetite and quartz. Adjacent to the iron-formation, quartz-bearing rusty horizons contain disseminated pyrite and magnetite.

The occurrences of loose sulphide-bearing blocks in the Inuarullikkat area, thought to be of local origin, suggest the area has a potential for sulphide mineralisation. The main sulphide is pyrite, both disseminated and as veins and veinlets in quartz-rich lithologies; some samples contain graphite. The studied samples have elevated values of Cu (741 ppm), Mn (1170 ppm), Ni (271 ppm), and Zn (272 ppm).

Graphite-pyrrhotite schist

Graphite-pyrrhotite schists are common in the supracrustal successions of the study area, of which the best known occurrence is the graphite deposit at Akuliaruseq (Fig. 2), which contains 1.6 million tonnes of ore grading 14.8% graphite and 6 million tonnes with 9.5% graphite (Bondam 1992; Grahl-Madsen 1994). The mineralisation is believed to be stratiform. Other graphite-bearing supracrustal rocks occur at Nordre Strømfjord (4; Fig. 2). Graphite layers in the schists range from 1–10 m in width, and are clearly concentrated in fold closures and within shear zones. Iron sulphides range from 1 to 5 vol.% in the most sulphide-rich parts of the schists, and gold is recorded in small amounts (10–100 ppb).

Mafic to ultramafic rocks

Small gabbroic bodies are found throughout the study region (5, 6, 7; Fig. 2). Locally they preserve well-developed magmatic layering and contain small amounts of magnetite, pyrite, pyrrhotite, and chalcopyrite. One gabbro body north of Ataneq (5), 300 × 400 m in size, is medium-grained, brownish weathering, and preserves magmatic banding as 1–5 cm wide light and dark bands. Some parts of the gabbro contain magnetite-bearing layers and occasional malachite staining is seen. The texture of the gabbro is similar to that of many of the magnetite-bearing amphibolites of the Attu and Ataneq regions.

A hitherto undescribed 10 × 30 m gabbroic body was found on the steep, eastern side of a small island north of Qasigiannguit (6), where it has tectonic contacts against the enveloping banded gneisses. The gabbro is coarse-grained and completely altered; medium- to coarse-grained magnetite occurs throughout the body, with the largest concentration in the centre of the alteration zone. Disseminated pyrite is found throughout the gabbro.

Isolated pods of ultramafic rock up to 30 m thick are common in the supracrustal units of the Ussuit region (7), where they are cut by SSW–NNE-trending joints parallel to the regional faults of the region. They are invariably pervasively altered to light green actinolite, and contain small amounts of interstitial iron sulphides.

Fig. 4. Banded iron-formation with magnetite and rusty pyrite-bearing mica gneiss zone at the fjord Inuarullikkat (locality 3 in Fig. 2).

Pegmatites

The gneisses throughout the study region are commonly cut by red-coloured pegmatites in which the K-feldspar crystals often reach more than 10 cm in size. These pegmatites occur as concordant and discordant bodies and bands up to 1 m across. Some contain conspicuous aggregates of magnetite, allanite and occasionally pyrite, but they do not seem to have any economic potential.

White-coloured pegmatites are less common than the red K-feldspar pegmatites, and contain minor contents of iron sulphides; up to 400 ppb gold was recorded in a composite chip sample from a sulphide-mineralised pegmatite from the Kangaatsiaq area. This type of pegmatite also carries monazite (Secher 1980).

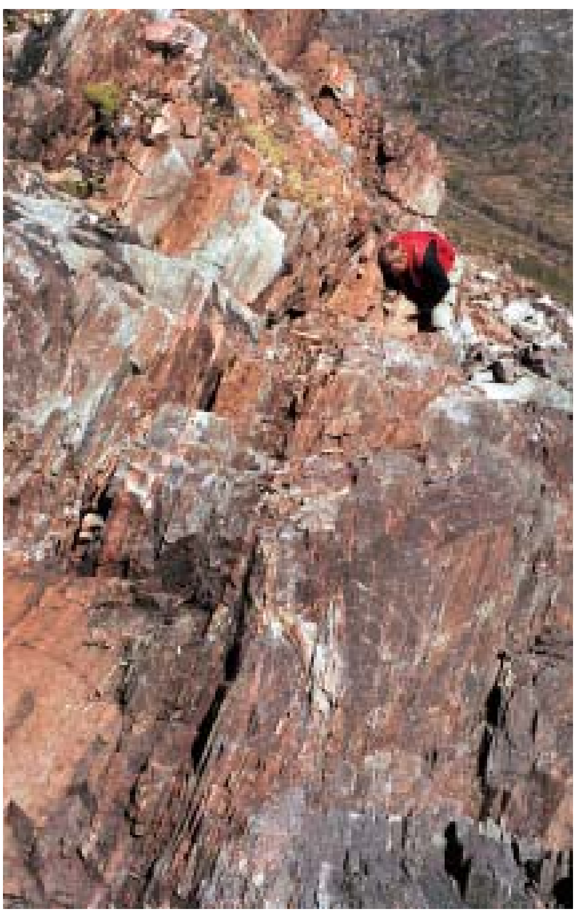

Fig. 5. Shear zone south of Attu (locality 8 in Fig. 2), with mylonite and associated magnetite, pyrite and gold mineralisation.

Shear zones

In the southern Attu area a 100–330 m wide mylonite zone (8; Fig. 2) cuts through granulite and high amphibolite facies gneisses, and forms part of a complex shear system consisting of three parallel fault systems striking NNE–SSW and dipping 60–70°W.

Gold-bearing *Ujarassiorit* samples originate from a coastal cliff along the mylonite and shear zone, which here consists of 5–20 cm wide bands of mylonite and a rusty band (10–20 cm thick) containing pyrite, magnetite and some chalcopyrite (Fig. 5). The host rock is grey gneiss, which is silicified at its contact with the mineralised zone. New samples collected in 2001 confirm gold contents of up to 4 ppm.

Fault zones

Mineralised faults occur between the inner parts of Kuup Akua (9; Fig. 2) and Ussuit. Semi-massive 5–10 cm thick lenses of pyrrhotite with pyrite and chalcopyrite occur along both margins of the central part of the fault zone, which is up to 5 m wide, with a high content of graphite. In a zone up to 100 m wide east of the fault zone, intense malachite staining occurs in supracrustal rocks in patches up to 2 m across (Fig. 6).

Prominent SSW–NNE-trending faults cut through all lithologies in the region, and are commonly characterised by red and green colouring due to conspicuous amounts of K-feldspar and epidote, which are related to zones of intense silicification along the fault planes (e.g. 10; Fig. 2).

A crush zone striking 030° occurs on the island Oqaatsut (11; Fig. 2). Along the main crush zone ankerite occurs on joints, and patches of malachite staining occur in the host gneiss. On north-east Oqaatsut the crush zone is locally up to 50 m wide and cuts gneiss, amphibolite and pegmatite. The crush breccia is clast supported (clasts 1–10 cm in size), veined by ankerite and silicified; joints are filled with epidote and chlorite. Several boudins (1 × 4 m) of amphibolite with small amounts of iron sulphides are enclosed in the crush zone.

Eqaluit 'supracrustals'

A thick NE–SW-trending amphibolite encloses a 5 m thick, rusty weathering garnet-quartz rock (garnetite) which hosts a sulphide mineralisation south of Eqaluit (12; Fig. 2). Pyrrhotite has been identified, and a light brown alteration is caused by haematisation associated with pervasive jointing.

Fig. 6. Fault zone in paragneiss in southern Kuup Akua. Malachite staining occurs in jointed, but unaltered country rock. The pattern of blocky jointing can be recognised in a several hundred metres wide zone along the trace of the fault (locality 9 in Fig. 2).

Quartz and carbonate veins

Gold-bearing quartz veins were found in an *Ujarassiorit* sample from an island south of Attu (13; Fig. 2), and this site was revisited in 2001. The quartz veins occur as concordant up to 30 cm thick veins and as 5–10 cm thick discordant veins; gold contents of up to 0.5 ppm have been recorded.

At Kangilinaaq on the northern shore of the fjord Kangersuneq (14; Fig. 2) an up to 15 m wide boudinaged metadolerite dyke can be followed along strike for several kilometres. The necks of the boudins are cross-cut by quartz-calcite veins (3–4 cm wide and up to 50 cm long) and pegmatites which contain disseminated sulphides and magnetite (less than 1 vol.%).

Lithological contacts

Contact zones between different lithologies are often the site of mineralisations, with locally up to one metre wide zones of mineralised host rocks containing disseminated pyrite (max. 5 vol.%) and magnetite (e.g. 15; Fig. 2). These appear to be associated with pegmatitic developments, which has led to enhanced sulphide contents in the host rocks as a consequence of remobilisation along the contacts.

On the Kangilinaaq peninsula a band of semi-massive pyrrhotite occurs in a reaction zone between mafic and supracrustal rocks. Spectacular rust horizons are also associated with an approximately 50 m thick, coarse-grained, hornblende-garnet-rich mafic unit containing disseminated magnetite and hematite (16; Fig. 2). This area has previously been targeted for prospecting by Kryolitselskabet Øresund A/S (Gothenborg 1980) and Nunaoil A/S (Petersen 1997).

Marble and calc-silicate-rich rocks

Marble and calc-silicate rocks occur in supracrustal sequences over most of the region. At a few localities (e.g. 17; Fig. 2) fluorite occurs in minor amounts in the marble and calc-silicate rocks, especially near the contacts with quartzo-feldspathic country rocks. Graphite is also a common accessory mineral, and is especially common in marbles on the north-west shore of Kuup Akua. In the Naternaq area, carbonate rocks are associated with the sulphide horizons (see Østergaard *et al.* 2002, this volume).

Summary

Amphibolites south of Ataneq have gabbroic textures and contain magnetite in thin layers of probable magmatic origin. The amphibolites and supracrustal rocks north of Ataneq are reminiscent of supracrustal sequences in the Naternaq area, but lack the carbonate and exhalite components. Carbonates are more common in the southern part of the study area (e.g. Kuup Akua). Exhalite rocks are known from the Naternaq area and from the area between Giesecke Sø and Ataneq in the vicinity of Nordre Strømfjord.

In the study region the only major mineral deposits known are the Naternaq pyrrhotite deposit and the Akuliaruseq graphite deposit. The former is further discussed by Østergaard *et al.* (2002, this volume).

Gold anomalies south of Attu appear to be related to both shear zones and quartz veins. Gold is also found in white pegmatite veins in the Kangaatsiaq area. Gold anomalies in the Attu area are related to shear zones associated with a complex fault system; the gold is associated with pyrite, chalcopyrite and magnetite.

Granite and pegmatite intrusions are often associated with sulphide and magnetite mineralisation in the adjacent host rocks.

Hydrothermal activity along NE–SW-trending lineaments seems to be responsible for sulphide and oxide mineralisation and secondary malachite staining. Crush and mylonite zones with carbonatisation (ankerite) and silicification characterise lineaments and fault zones. Narrow zones of silicification are common throughout the study region.

None of the presently known mineral occurrences seem to have economic potential. The sulphide occurrences are dominated by pyrrhotite with only minor pyrite and chalcopyrite.

Acknowledgements

The skipper and crew of M/S *Søkongen* are thanked for good seamanship and much practical help.

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Authors' addresses

H.S., S.M.J., M.L., B.M.N. & L.T., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* E-mail: *hst@geus.dk*

J.B., *Bureau of Minerals and Petroleum, P.O. Box 930, DK-3900 Nuuk, Greenland.*

H.B.M., *Geological Institute, University of Aarhus, DK-8000 Århus C, Denmark.*

C.Ø., *Aggersvoldvej 15, 2. tv., DK-2700 Brønshøj, Denmark.*

Geological correlation of magnetic susceptibility and profiles from Nordre Strømfjord, southern West Greenland

Bo M. Nielsen and Thorkild M. Rasmussen

The Palaeoproterozoic Nagssugtoqidian orogen is dominated by reworked Archaean gneisses with minor Palaeoproterozoic intrusive and supracrustal rocks. The Nagssugtoqidian orogen (Fig. 1) was the focus of regional geological investigations by the Geological Survey of Denmark and Greenland (GEUS) in 2001 (van Gool *et al.* 2002, this volume). In conjunction with this project, geophysical studies in the inner part of Nordre Strømfjord, Kuup Akua and Ussuit were undertaken as part of the Survey's mineral resource assessment programme in central West Greenland. The studies include geophysical modelling of airborne magnetic data, follow-up studies of aeromagnetic anomalies by magnetic ground surveying, and geostatistical treatment and integration of different geological, geophysical and geochemical data. The aim is to obtain an interpretation of the region in terms of both regional geological features and modelling of local features of relevance for the mineral resource assessment. This paper presents an account of the field work and some of the new data.

The work was carried out from a rubber dinghy in the fjords and from helicopter-supported inland camps. *In situ* measurements of the magnetic susceptibility of rocks and magnetic ground profiles were carried out during a period of 25 days in June and July 2001. In total 133 localities were visited from three camps.

The data collected will be used together with magnetic properties and density of rock samples determined in the laboratory for geophysical modelling of the area. The petrophysical data will constrain the geophysical and geological interpretations and thus provide a higher degree of confidence in the models.

Magnetic susceptibility

Magnetisation is defined as the magnetic moment per unit volume. The total magnetisation of a rock is the vector sum of the remanent magnetic moment that exists irrespective of any ambient external magnetic field, and the induced magnetic moment that exists because of the presence of the external magnetic field. The strength and direction of the induced magnetic moment is proportional to the strength and direction of the external magnetic field. The proportionality factor is termed the magnetic susceptibility (denoted with the symbol χ and assumed to be a scalar quantity). In the following sections all quantities are referred to the SI system (Système International) in which the magnetic susceptibility becomes dimensionless.

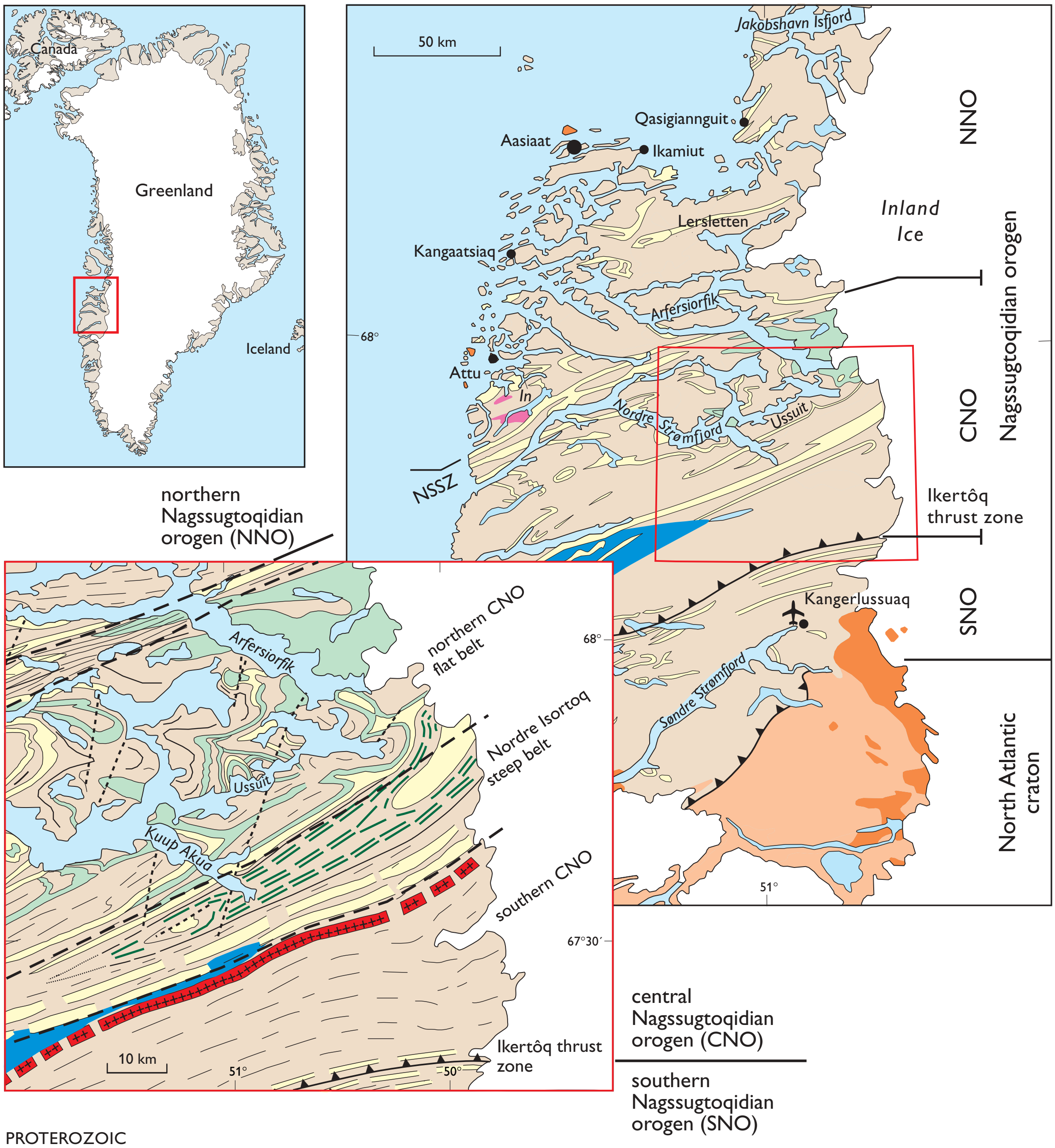
The magnetic susceptibility of rocks was measured with a hand-held magnetic susceptibility meter (Fig. 2). To obtain estimates of the remanent magnetic component and more precise results of the magnetic susceptibility it is also necessary to investigate rock samples in the laboratory. The *in situ* measurements presented in this paper were obtained during the field work; the results of laboratory investigations currently being carried out at the petrophysical laboratory at the Geological Survey of Finland are not yet available.

The amount and distribution of the magnetic minerals in a rock determine the magnetic response measured along a profile. The content of magnetite (Fe_3O_4) and its solid solution ulvöspinel (Fe_2TiO_4) is the dominating factor in crustal rocks (Blakely & Connard 1989). The magnetic susceptibility of gneiss is normally between 0.1×10^{-3} SI and 25×10^{-3} SI (Telford *et al.* 1998).

Data acquisition and processing

The magnetic susceptibility meter used in the field was a Geo Instrument GMS-2 (Fig. 2). Depending on the homogeneity of the rocks and the size of the outcrop, ten to forty readings were taken at each locality to ensure a proper statistical treatment of the measurements. Outcrops were selected so as to provide the most representative measurements of the rock on unweathered, smooth surfaces. In total 3444 readings were taken at the 133 localities. In the statistical treat-

Geology of Greenland Survey Bulletin 191, 48–56 (2002)



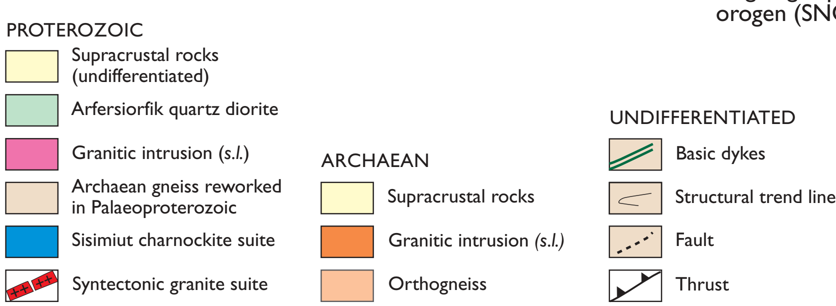


Fig. 1. Simplified geological map of the study region and the Nagssugtoqidian orogen, southern West Greenland. The geological subregions (northern CNO flat belt, Nordre Isortoq steep belt, southern CNO) are also shown. Modified from van Gool *et al.* (1996, 2002, this volume).
NSSZ: Nordre Strømfjord shear zone; **In**: Inuarullikkat.

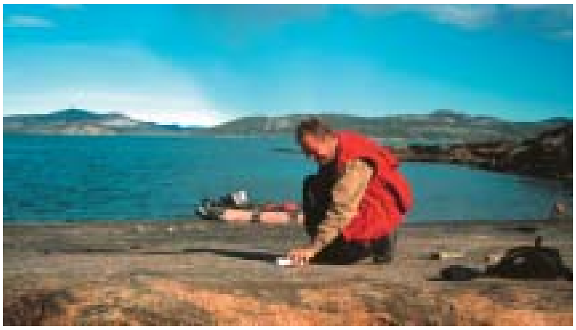


Fig. 2. The hand-held magnetic susceptibility meter is small and easy to use. Measurements are taken first with the meter at the rock surface, followed by a reference reading with the meter held up in the air. The photograph shows the first step of the measurements on typical gneiss lithologies in the central part of Ussuit fjord.

ment the measurements were grouped according to locality, rock type and geological province. In cases of very heterogeneous rocks, the relative proportions of the rock types present were estimated and data weighted accordingly. Magnetic susceptibility measurements were also made as a secondary task by two other field teams in the western part of Nordre Strømfjord, at Attu, in the Ikamiut area and at Lersletten, but these data are not included in this presentation.

Two long magnetic profiles were made (Fig. 3) with measurements of both the total field and the vertical gradient using a magnetic gradiometer (Geometrics G-858); another magnetometer (Geometrics 856) was used as base magnetometer. The sampling distance along the profiles was approximately 1 m. As an example, the magnetic total field intensity from the south-

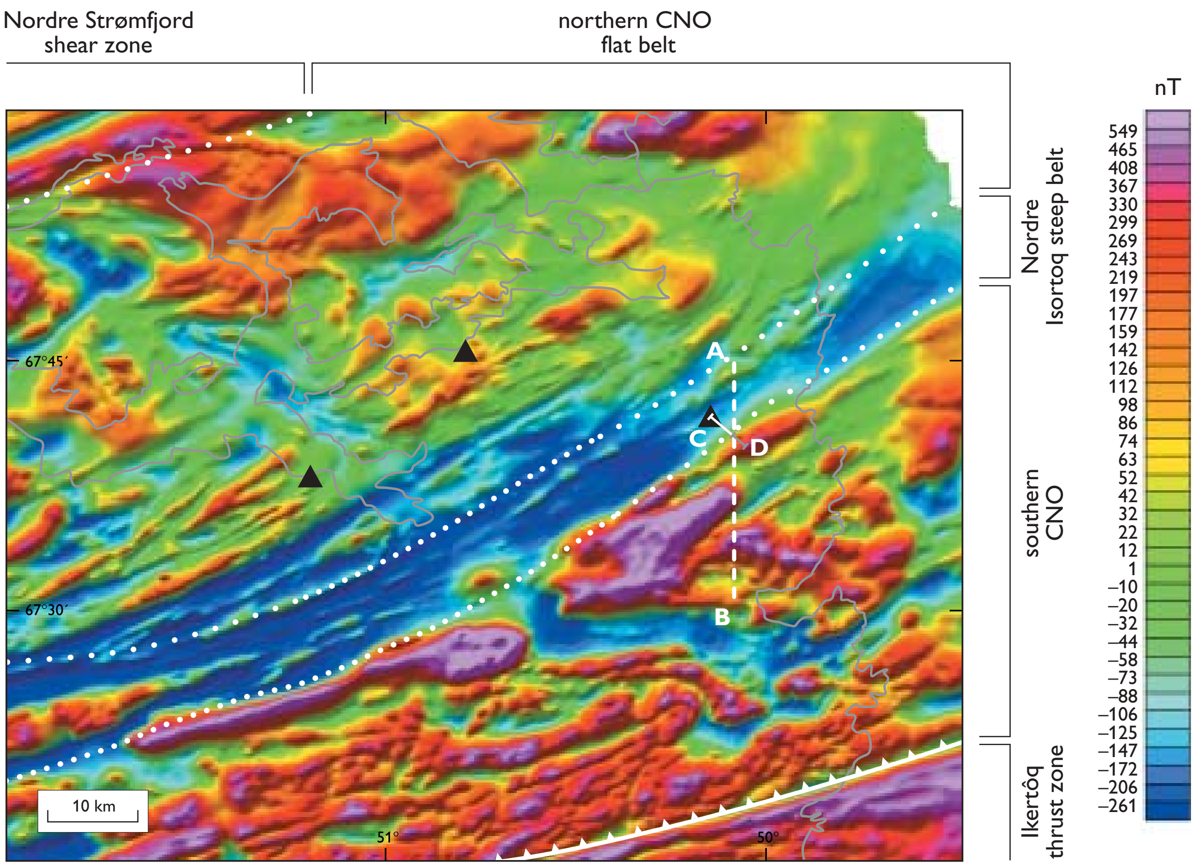


Fig. 3. Magnetic total-field intensity map with shaded relief. The tectonic boundaries and subregions of the central Nagssugtoqidian orogen stand out as distinct lineaments and zones in the magnetics. Shading is with illumination from the north-north-west. **Black triangles** mark the position of the three field camps in the study area. **Dotted lines** mark the boundaries within the central Nagssugtoqidian orogen. **Closely spaced dots** indicate boundaries mapped in the field, and **wider-spaced dots** extrapolations based on the aeromagnetic data. The airborne and ground magnetic profiles are shown with **dashed** (A–B) and **full white lines** (C–D), respectively. The part of the ground profile used for modelling is shown as the **grey part** of the line C to D (see also Fig. 5).

ernmost two kilometres of the profile undertaken from the eastern inland camp south of Ussuit is discussed in a later section.

Regional geology

Reworked Archaean gneisses with minor Palaeoproterozoic supracrustal and intrusive rocks dominate the Nagssugtoqidian orogen. The region studied in this paper lies in the eastern part of the central Nagssugtoqidian orogen (CNO; Marker *et al.* 1995). The CNO is bounded by the Nordre Strømfjord shear zone to the north and the Ikertôq thrust zone to the south (Fig. 1).

The CNO can be divided into three *subregions*: (1) the northern CNO flat belt; (2) the Nordre Isortoq steep belt; and (3) the southern CNO (van Gool *et al.* 1996; Connelly & Mengel 2000).

Subregion 1. The rocks of the northern CNO flat belt are dominated by Archaean orthogneisses with a grey to white colour and variably developed banding; major open upright antiformal structures are characteristic. The gneisses are intercalated with narrow belts of Palaeoproterozoic supracrustal rocks, spatially associated with the calc-alkaline Arfersiorfik intrusive suite. The supracrustal rocks are often strongly foliated and migmatised with several leucosome phases, and comprise mafic amphibolite bodies and layers, ultramafic bodies, pelitic schists, marble and calc-silicate rocks, and fine- to medium-grained quartz-rich paragneisses with biotite and garnet.

Subregion 2. The Nordre Isortoq steep belt separates the northern CNO flat belt and the southern CNO. The steep belt is a zone of steeply dipping and isoclinally folded orthogneiss and paragneiss, and is dominated by an up to five kilometres wide belt of supracrustal rocks. The supracrustal rocks comprise mainly pelitic and psammitic paragneisses, with lesser amounts of mafic to ultramafic bodies and layers, amphibolites and calc-silicate rocks. The gneisses are very variable in appearance, and range from felsic migmatitic gneiss types to more pelitic and mafic types. The rocks are in granulite facies.

Subregion 3. The southern CNO consists dominantly of homogenous orthogneisses.

The study region is cross-cut by several NE–SW-trending faults of unknown age. The rocks to the west of Kuup Akua and north of the northern border of the Nordre Isortoq steep belt, including the Ussuit area, are all in amphibolite facies. The rocks to the east of Kuup Akua and further north are in granulite facies.

Regional aeromagnetic data

The aeromagnetic anomaly data for the study region resulting from project *Aeromag 1999* (Rasmussen & van Gool 2000) were obtained by subtraction of the International Geomagnetic Reference Field (IGRF) from the measured data, and correlate well with the surface geology of the region (Figs 1, 3).

The subdivision of the CNO and the boundary features are clearly reflected in the aeromagnetic anomaly data. The Nordre Strømfjord shear zone stands out as a sharp discontinuous ENE–WSW lineament. Magnetic domains can also be recognised coinciding with the three geological subregions.

Subregion 1. The northern CNO flat belt is characterised by elongated and curved, short wavelength anomalies reflecting the folded nature of this domain. These anomalies are superimposed on a regional magnetic field level of around zero.

Subregion 2. The Nordre Isortoq steep belt stands out as an ENE–WSW-trending regional magnetic low with superimposed low amplitude, elongated, short wavelength anomalies. Based on the magnetic data alone, it may be argued that the northern border of the steep belt should be placed more northerly than that depicted in Fig. 3, for which only the central part has so far been confirmed by mapping. The low magnetic anomaly is partly due to the presence of supracrustal rocks. Uniform low magnetic response of supracrustal rocks is confirmed from many other regions of the world (Card & Poulsen 1998).

Subregion 3. The southern CNO has a high magnetic regional level and is characterised by closely spaced short wavelength anomalies with steep horizontal gradients. Several fold structures can be recognised in the magnetic anomaly patterns. A NNW–SSE-trending low magnetic feature cross-cuts the eastern part of the southern CNO. The anomaly is weak in the steep and flat belt regions.

The border between the CNO and the southern Nagssugtoqidian orogen (SNO; Fig. 1; van Gool *et al.* 2002, this volume) stands out as a very sharp and large gradient, which can be correlated with the Ikertôq thrust zone.

Magnetic susceptibilities of different rock types

The magnetic susceptibility measurements presented here show that the different rock types exhibit a wide range of susceptibility values within the same formation, and even on the same outcrop. The measurements for the main rock types of the studied area are given in Fig. 4 and Table 1.

The susceptibility in SI units for the entire data set ranges from 0.0 to 91.41 × 10^{-3} SI. The rock types examined include orthogneisses, paragneisses, a variety of supracrustal rocks, and intrusives related to the Arfersiorfik quartz diorite. The highest values correspond to orthogneisses, whereas some marbles and gneisses are virtually non-magnetic.

Gneiss

The susceptibility distribution for all types of gneisses is shown in Fig. 4A. In total, 2372 measurements were made on 77 gneiss localities. The variability of the gneisses in the field is reflected in very variable magnetic susceptibilities ranging from 0.0 to 68.18 × 10^{-3} SI, with a geometric mean value of about 1.21 × 10^{-3} SI. The negative skewness (Table 1) of the measurements in Fig. 4A shows an asymmetric tail extending towards lower values. This may reflect that the generally low measured susceptibility values have a too low mean, perhaps due to near-surface weathering of the rocks.

In general, the metamorphic facies is reflected in the susceptibility values, with high values for granulite facies gneisses and lower values for amphibolite facies gneisses. This is probably caused by the formation of magnetite under granulite facies metamorphism (Clark 1997). Moreover, the gneiss type is clearly reflected in the susceptibility values, with low values for paragneisses and higher values for orthogneisses. Visible magnetite was often observed in migmatites, which possibly indicates formation of magnetite during migmatisation, and is reflected in the high susceptibility values.

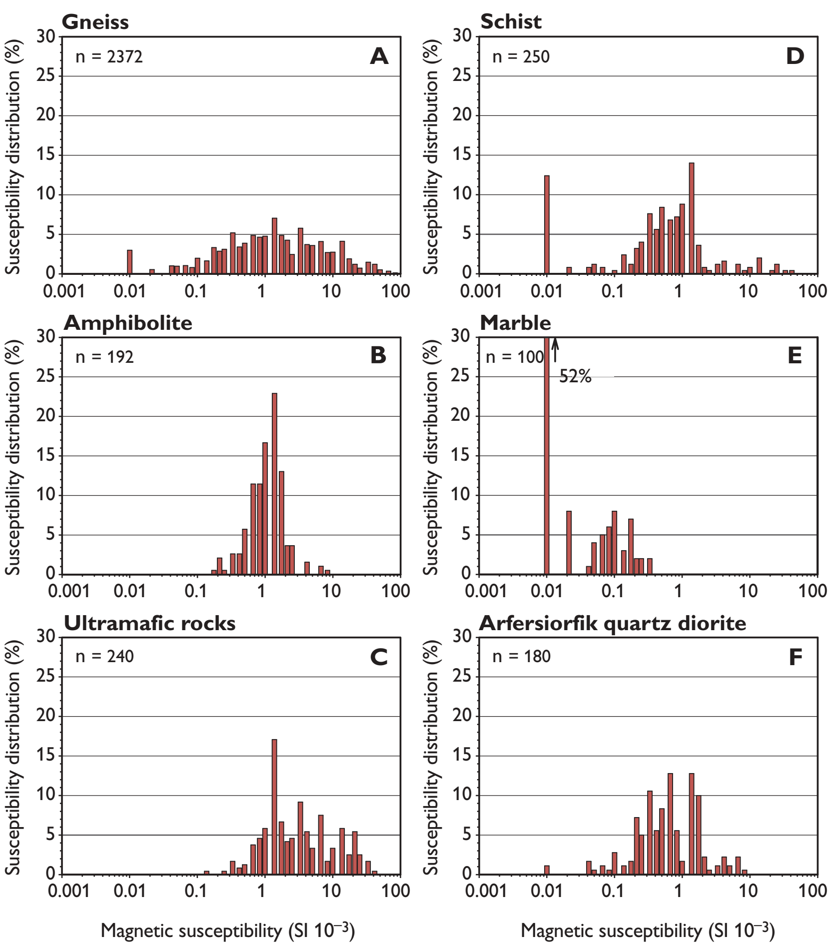


Fig. 4. Magnetic susceptibility distribution in per cent for different rock types.

Table 1. Measurements of magnetic susceptibility

Rock type	Number of measurements	Minimum SI x 10^{-3}	Maximum SI x 10^{-3}	Geometric mean SI x 10^{-3}	Skewness
Gneiss	2372	0.00	68.18	1.21	–0.12
Amphibolite	192	0.17	7.33	0.94	–0.02
Ultramafic rocks	240	1.00	19.44	2.75	1.92
Schist	250	0.00	34.70	0.59	0.21
Marble	100	0.00	0.30	0.05	–0.29
Arfersiorfik quartz diorite	180	0.69	6.88	0.53	–0.45

The skewness characterises the degree of asymmetry of a distribution around its mean. The geometric mean is the mean of all the obtained susceptibility values larger than zero for the given rock type.

Amphibolite

Measurements of magnetic susceptibility of mafic amphibolite (Fig. 4B) were taken at eight localities, and give a susceptibility range from 0.17 × 10^{-3} SI to 7.33 × 10^{-3} SI. The amphibolites are characterised by fairly uniform distribution of the values with a geometric mean of 0.94 × 10^{-3} SI. These susceptibility values are typical for amphibolite, reflecting their mafic, paramagnetic mineralogy (Henkel 1991; Clark 1997). The highest values were obtained from amphibolites within gneiss lithologies, and the lowest values from amphibolites in supracrustal sequences.

Ultramafic rocks

The susceptibility distribution for ultramafic rocks is shown in Fig. 4C. Compared to the mafic amphibolites, the ultramafics have higher susceptibility values ranging from 1.0 to 19.44 × 10^{-3} SI for seven localities. The high values reflect the high iron content of the ultramafic rocks. Despite the high skewness (Table 1), the high values are in accordance with general values for ultramafic rocks (Clark 1997). Some of the highest values were obtained on magnetite-rich reaction rims along contacts with the neighbouring rocks. The ultramafic rocks are often heavily altered, which can explain some of the lower susceptibility values obtained.

Schist

The susceptibility values for mica schists range from 0.0 to 34.7 × 10^{-3} SI (Fig. 4D) taken at eight localities. Susceptibility values obtained for pelitic schists were higher than for more psammitic schist types; higher iron content of the pelitic schists in an oxidising environment favours metamorphic formation of magnetite. It should be noted, however, that both pelitic and psammitic schists at several localities had a large content of graphite. The carbon from the graphite can

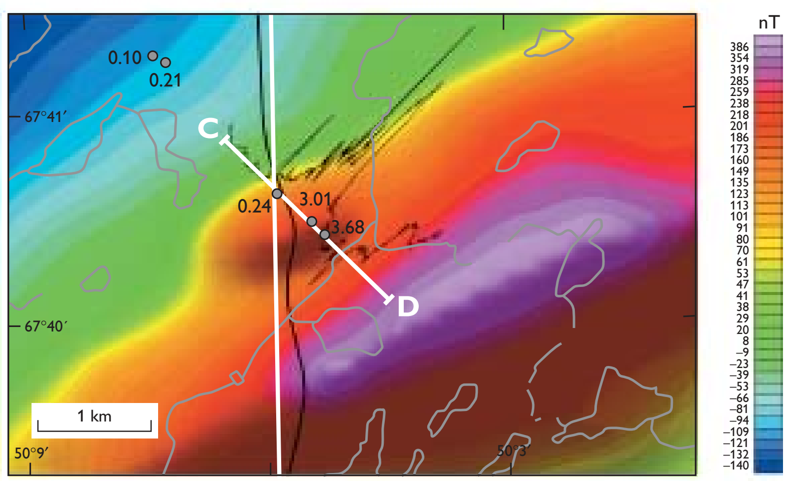


Fig. 5. Magnetic total-field intensity map with shaded relief. The response observed from the airborne and ground magnetic survey profiles south of Ussuit (see Fig. 1). The NNW–SSE-trending **white line** C–D shows the location of the ground profile. The N–S-trending **white line** is the airborne magnetic profile. The white lines also define the zero level for the magnetic total field intensity data shown as a **black curve**. The **grey circles** show locations where selected susceptibility values were obtained in the field.

have a reducing effect, which hinders the formation of magnetite. As was the case for the amphibolites, the negative tail of the distribution possibly reflects weathered rocks.

Marble

Marbles from five localities are very similar, all with very low susceptibility values (Fig. 4E) due to the high content of non-magnetic calc-silicate minerals. The highest values for marble were obtained at one locality where the marble contained thin intercalated mafic mica schist bands and was penetrated by pegmatite veins. In general, the magnetic susceptibility is almost negligible, and the marble lithologies can thus be considered as forming non-magnetic units.

Intrusive rocks: Arfersiorfik quartz diorite

Susceptibility values were taken at six outcrops of the Arfersiorfik quartz diorite, and fall into two groups (Fig. 4F). The first group has high values ranging from 0.69 to 6.88 × 10^{-3} SI, while the second group has lower values between 0.01 and 1.10 × 10^{-3} SI. Field observations indicate that the quartz diorite varies in appearance from dark to light coloured types, due to varying amounts of mafic components, quartz content and grain size, which may explain the variance of the susceptibility values.

Magnetic profile data

The NNW–SSE profile measured from the eastern inland camp south of Ussuit is perpendicular to the southern border of the Nordre Isortoq steep belt (line C to D in Figs 3, 5). The profile runs from the low magnetic zone of the steep belt into a more irregular high magnetic anomaly zone. The profile was laid out as a straight line, with start and end points together with every 100 m interval determined by use of the Global Positioning System (GPS).

The central part of this ground profile crosses a small positive anomaly. One of the aims was to compare the details obtained from the ground measurements with a profile from the *Aeromag 1999* survey (Rasmussen & van Gool 2000). The airborne magnetic profile was flown at an altitude of 300 m, runs N–S and intersects the ground profile (Fig. 5). The difference in content of short wavelength anomalies in the two survey types (Fig. 5) clearly illustrates the attenuation with increased distance to the sources, which has significant implications for the amount of detail that can be acquired from the airborne data. However, a clear correlation with the observed surface geology is confirmed by the ground profile.

The sharp positive anomalies observed in the central part of the ground profile correlate with a 100–150 m wide zone containing ultramafic rocks, whereas the lower magnetic anomalies reflect gneiss lithologies. The locations of the lowest anomalies can be related to calc-silicate horizons observed in the field. Based on these observations it can be concluded that the small positive anomaly in the aeromagnetic data originates from the presence of ultramafic rocks.

Combined forward modelling and inversion undertaken with tabular bodies as the principal model is shown in Fig. 6 for both the ground and airborne profile. The free parameters in the final inversion are location, size, thickness and magnetic properties. Some initial modelling with the dip angle as free parameter indicates that a steep northward dip of the bodies gave the best data-fit. In the final inversion the dip angles for all bodies were identical, except one body for which it was necessary to deviate slightly from the common angle in order to obtain a proper data-fit. The relatively thin alternating bodies of rocks with different magnetic properties, necessary in the modelling, reflect the banded nature of the geology in the study region.

To test the agreement of the field susceptibility measurements with the values obtained by the modelling, the modelling was undertaken without any constraints on the magnetic properties, but with the assumption that the direction of magnetisation was aligned along the present direction of the geomagnetic field. Thus the modelling does not distinguish between a remanent magnetisation in the direction of the geomagnetic field and the induced magnetic component. The magnetic susceptibility values for the bodies in the modelling range from 0 to 92 x 10^{-3}, with a mean around 30 x 10^{-3}. This is one order of magnitude higher than the geometric mean values of the measured susceptibility values, but within the range obtained from the measured values. An explanation to this discrepancy may be that the remanent magnetic component contributes considerably to magnetisation; however, this has not been confirmed by laboratory measurements on rock sample from the Survey's archive.

Although modelling of potential field data is known to be highly ambiguous, the model presented above includes features that are expected to be common to all

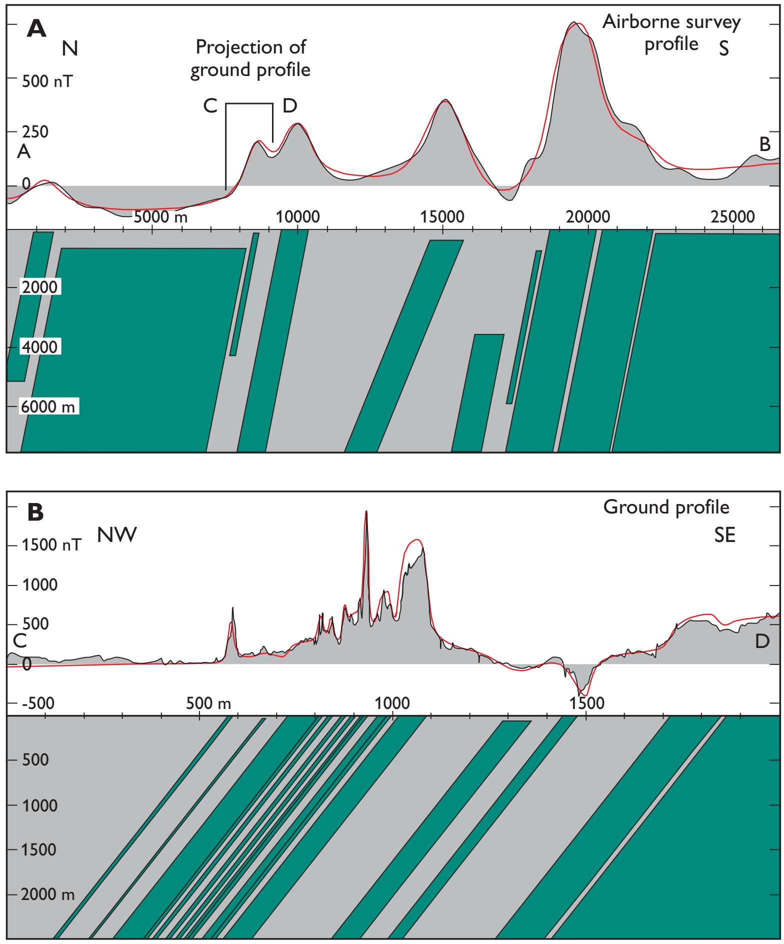


Fig. 6. **A**: The airborne profile data (A–B, the dashed white line in Fig. 3) and the resulting model from the modelling with the projection of the ground profile (line C–D in Figs 3, 5). **B**: The ground profile data and the resulting model from the modelling. Measured magnetic total field intensity data are shown in **black**, and the response of the models in **red**. **Green-coloured bodies** are the magnetic bodies used to model the measured data. The grey shaded regions in the model correspond to magnetic reference level; i.e. zero magnetic susceptibility.

models that are realistic representations of the geology. More detailed modelling and further study including measurements of the magnetic properties are warranted.

Conclusions and further work

The aeromagnetic data reflect the regional geology well. Further work will involve interpretation through processing and modelling.

The ongoing construction of a large database of magnetic susceptibilities and other petrophysical parameters, coupled with observations on rock types and structures, will help to elucidate the correlation between the geology and magnetic responses, and is a prerequisite for realistic geological interpretations of the aeromagnetic surveys from the area.

The field measurements show that the magnetic susceptibility is variable within the same rock type, and even on individual outcrops there are considerable variations. Gneiss and schist lithologies in particular have very variable susceptibilities, probably reflecting the variable nature of the lithologies, e.g. pelitic to psammitic. Ultramafic rocks and amphibolites, and to a lesser extent some intrusives of the Arfersiorfik quartz diorite suite, show relatively high magnetic susceptibilities within a narrow range. Marble is essentially a non-magnetic rock type. All susceptibility values obtained from the different lithologies are within the typical range for such rock types (Clark & Emerson 1991; Shive *et al.* 1992; Clark 1997; Telford *et al.* 1998), and are in agreement with values obtained in previous investigations (Thorning 1986). The variable susceptibility values of the rock types reflect the different nature of the rocks and their different geological histories, e.g. metamorphism, hydrothermal alteration, bulk composition, etc. More work will be necessary to analyse the susceptibility values in relation to these factors. The discrepancy between the susceptibility values obtained in the field and those indicated by modelling will also have to be investigated further. The ground magnetic profile carried out during the field season illustrates well the significant difference in resolution of the geological details that are possible from different survey types, at the same time confirming the correlation of geology and airborne anomalies.

The investigations will continue in the 2002 field season, when ground geophysical surveys will be undertaken in connection with lineament studies and the study of a mineralised horizon in amphibolite at the fjord Inuarullikkat (Stendal *et al.* 2002, this volume). The database of the magnetic susceptibility of rocks will be supplemented with new measurements and with laboratory determinations of petrophysical properties when these become available.

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *bmn@geus.dk*

Kimberlites and other ultramafic alkaline rocks in the Sisimiut–Kangerlussuaq region, southern West Greenland

Sven Monrad Jensen, Henriette Hansen, Karsten Secher, Agnete Steenfelt, Frands Schjøth and Thorkild M. Rasmussen

The alkaline province of southern West Greenland includes swarms of dykes described as kimberlites and lamproites (Larsen 1991), and these rock types are widely distributed in the Sisimiut–Sarfartoq–Kangerlussuaq region (Figs 1, 2). Kimberlites and lamproites are potential carriers of diamond, and since the description of the Sarfartoq carbonatite complex and the kimberlitic dykes related to this complex (Larsen 1980; Secher & Larsen 1980), the Sisimiut–Sarfartoq–Kangerlussuaq region has seen several campaigns of commercial diamond exploration. The latest and most persistent stage of exploration began in the mid-1990s and has continued to date, with varying intensity. Numerous reports of diamond-favourable indicator minerals from till sampling, finds of kimberlitic dykes, and recovery of actual diamonds from kimberlitic rocks have emerged since 1995 (Olsen *et al.* 1999). A drilling programme in late 2001 confirmed the unusually great length and width of a magnetic kimberlitic dyke (Ferguson 2001).

The alkaline ultramafic dykes within the Sisimiut–Kangerlussuaq and Sarfartoq regions intrude the border zone between the Archaean craton and the Palaeoproterozoic Nagssugtoqidian orogen (van Gool *et al.* 2002, this volume). This border is defined as the southern boundary of Palaeoproterozoic reworking of the Archaean basement gneisses. The reworking has affected the Palaeoproterozoic Kangâmiut dolerite dykes, which

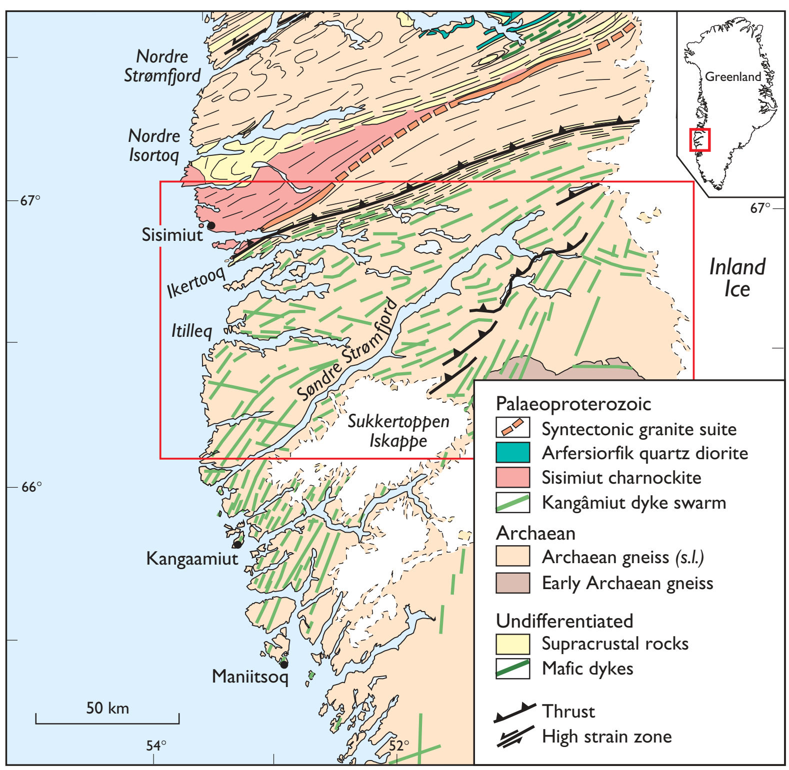

Fig. 1. Geological map of the region with the project area (Fig. 2) outlined in a **red frame**. Modified from Mengel *et al.* (1998).

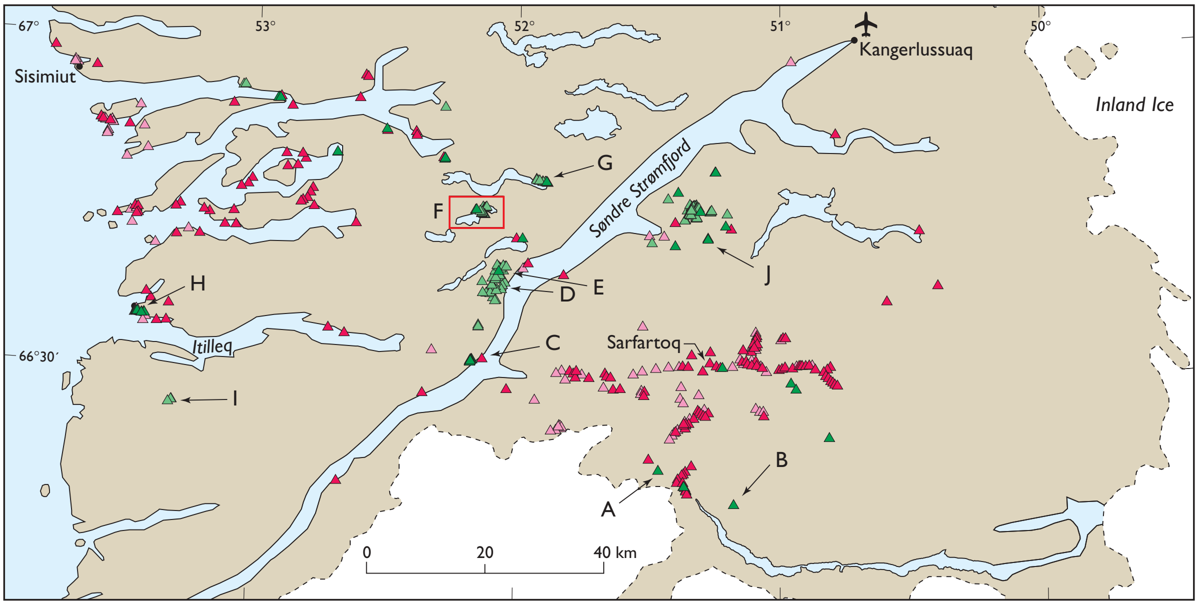

Fig. 2. Distribution of kimberlitic and lamprophyric occurrences within the project area. **A–J** are localities mentioned in the text. **Red triangles** are kimberlitic and lamprophyric dykes known prior to the present study: lamproites predominate in the region between Sisimiut and Itilleq, kimberlites in the Sarfartoq region (Larsen & Rex 1992). **Green triangles** are observations from the present study. **Heavy colouring** represents *in situ* finds and **light colouring** represents boulders (float).

were intruded into the Archaean gneisses prior to deformation and are now highly strained and boudinaged north of the boundary.

The intrusion of alkaline dykes appears to have taken place during two events. Lamproite dykes in the Sisimiut region are around 1.2 Ga old, whereas the Sarfartoq complex (Fig. 2) and a swarm of associated kimberlitic dykes have ages of around 0.6 Ga (Larsen & Rex 1992). A precise spatial relationship between the two intrusive events has not been established.

A project concerned with general scientific aspects of kimberlitic and related rocks in the Sisimiut–Kangerlussuaq region was established in 2000. The aim is to gather knowledge from companies' exploration activities and to incorporate Survey expertise such as petrology, structural geology, isotope geology, geochemistry, geophysics and the geographic information system (GIS). Field work was carried out in 2000 and 2001, with the Kangerlussuaq International Science Support (KISS) centre at Kangerlussuaq airport as logistical base. A combination of daily reconnaissance covering large areas using a helicopter, and fly camps of 2–3 days duration was applied.

The broad term 'kimberlitic' is used here in acknowledgement of the fact that the classification of the ultramafic dyke rocks of West Greenland is not resolved with unanimity. Many of the dyke rocks resemble kimberlites and have previously been described as such (Larsen 1980, 1991; Scott 1981; Larsen & Rex 1992). Mitchell *et al.* (1999), however, take the view that the dyke rocks are not 'archetypal' kimberlites, but ultramafic lamprophyres that should be termed melnoites or aillikites. In the light of the actual occurrence of diamonds in the West Greenland dyke rocks, Mitchell *et al.* (1999) consider them to represent one of the few examples of diamond-bearing ultramafic lamprophyres. One of the aims of the present project is to contribute to a generally accepted classification of the West Greenland kimberlitic and related rocks.

Distribution of kimberlitic and related rocks

Larsen's (1991) compilation of Greenland's kimberlite, lamproite and ultramafic lamprophyre occurrences proved to be a valuable initial guide to companies when the ongoing diamond exploration commenced in West Greenland in the mid-1990s (Olsen *et al.* 1999). The compilation includes data collected by earlier workers (e.g. Scott 1981), who typically operated by boat and thus were often restricted to working near the coast. As a consequence, the known occurrences had an uneven distribution, and some areas appeared to be without occurrences.

Many of the occurrences of *in situ* dykes and boulders (float) in the Sisimiut–Sarfartoq–Kangerlussuaq region known at present are indicated in Fig. 2. The approximately 600 occurrences include those from Larsen's (1991) compilation and new localities added by exploration companies and recent field work by the Geological Survey of Denmark and Greenland (GEUS). It should be noted that the map does not include a large number of company localities that are at present confidential because they lie within active exclusive exploration licence areas. The map illustrates the concentration of occurrences in the vicinity of the Sarfartoq carbonatite complex, which Larsen (1980) interpreted as a swarm of kimberlitic cone-sheets centred on the carbonatite.

Bedrock exposure is generally poor in the study region, and dykes and sills of kimberlite, lamproite and carbonatite can be difficult to trace because they are thin, easily eroded and often covered by overburden and vegetation. Therefore, both stream geochemical data and aeromagnetic data are investigated with the aim of identifying geochemical and geophysical signatures reflecting occurrences of kimberlitic and related dykes.

Field activities

Field work in 2000 consisted of one week's reconnaissance and visits to new dyke occurrences discovered by exploration companies. The 2001 field work was focused on the spatial distribution of kimberlitic dyke rocks in areas with little or no previous information, and detailed studies on mantle xenoliths from the kimberlitic dykes. Studies of mantle xenolith-bearing rocks are described in a separate section below. The field work also included testing the ease of locating occurrences described in companies' assessment reports using various Global Positioning System (GPS) equipment and GIS methods.

Locality F (Fig. 2) provides an example of the density of new observations made in an area with no previously reported kimberlitic or lamproitic occurrences. Within the framed area 26 kimberlitic boulders and one new dyke were registered (Fig. 3). Three of the boulders measure about 1 × 1 × 1 m in size, indicating that the dyke or dykes from which they originated must be of substantial dimensions. Several large boulders were broken up into many smaller fragments, resulting in a much higher count of individual pieces of kimberlitic rock. The high number of kimberlitic boulders in this small area suggests they may have been derived from a nearby dyke outcrop. Similar observations were made at localities G and H (Fig. 2).

Stream sediment geochemical anomalies reflecting alkaline rocks

Geochemical reconnaissance-scale stream sediment surveys have been carried out over large parts of West Greenland, including the project region considered here. The chemical analyses have been compiled and

Fig. 3. View of the area of locality F. A small outcrop of a new kimberlitic dyke (**arrow**) is located in the lineament marked by **dotted line**. Length of dotted line is approximately 200 m.

Table 1. Range of Nb concentrations of various rock types in the Sisimiut–Sarfartoq–Kangerlussuaq region

Rock type	Age	Nb ppm
Gneiss	Archaean	0.5–11
Charnockite	1.9 Ga	1–25
Syenite	1.9 Ga	5–25
Lamproite	1.2 Ga	95
Kimberlite	0.6 Ga	163–311
Beforsite	0.6 Ga	151
Carbonatite	0.6 Ga	2.3–22

From Larsen & Rex (1992) and GEUS database (unpublished).

calibrated (Steenfelt 1999, 2001a), and presented in a geochemical atlas of West and South Greenland (Steenfelt 2001b). The atlas displays element distribution patterns for 43 major and trace elements based on analysis of the < 0.1 mm grain size fraction of stream sediment samples collected systematically with a density of about one sample per 30 km^2. The atlas also includes maps of high-pressure mineral phases of assumed mantle derivation, so-called kimberlite indicator minerals, identified in the 0.1 to 1 mm fraction of stream sediment samples collected between latitudes 61°N and 67°N.

The Sarfartoq carbonatite complex comprises rocks enriched in P, Ba, Sr and rare-earth elements (REE), and hosts a niobium-rich pyrochlore mineralisation (Secher & Larsen 1980). In the geochemical maps, the Sarfartoq complex is easily recognised as a local but very pronounced anomaly with high concentrations of P, Ba, Sr, Nb and REE, as well as Mo, Ta and Th.

Kimberlites and lamproites have olivine- and carbonate-rich groundmass (high Mg and Ca) and high concentrations of the trace elements Ba, Cr, Ni, Nb, Sr, P, Ti and light REE. In view of the particular mineralogy and chemistry of the alkaline rocks, their presence within the gneiss-dominated Archaean basement should be readily detectable in the stream sediment geochemical survey. However, because of the small volume of alkaline rocks, their geochemical imprint on the stream sediment composition may be obscured by the presence of other igneous rocks that have intruded the tonalitic gneisses in the same region. Gabbroic inclusions within the gneisses, and the Palaeoproterozoic Kangâmiut dolerite dyke swarm, release so much Ni, Cr and Ti to the streams that the contribution of these metals from alkaline ultramafic rocks is easily disguised. Furthermore, Palaeoproterozoic intrusions within the Nagssugtoqidian domain comprise considerable volumes of charnockite and syenite, enriched in Ba, Sr, P and REE (Steenfelt 1997), which give rise to anomalies that are similar to those expected to be caused by kimberlites and lamproites.

However, one element, niobium, has proved convincing as a 'pathfinder' for kimberlites and lamproites. Table 1 illustrates the high Nb concentrations of kimberlites and lamproites relative to Archaean gneisses; even the Palaeoproterozoic syenites have relatively low

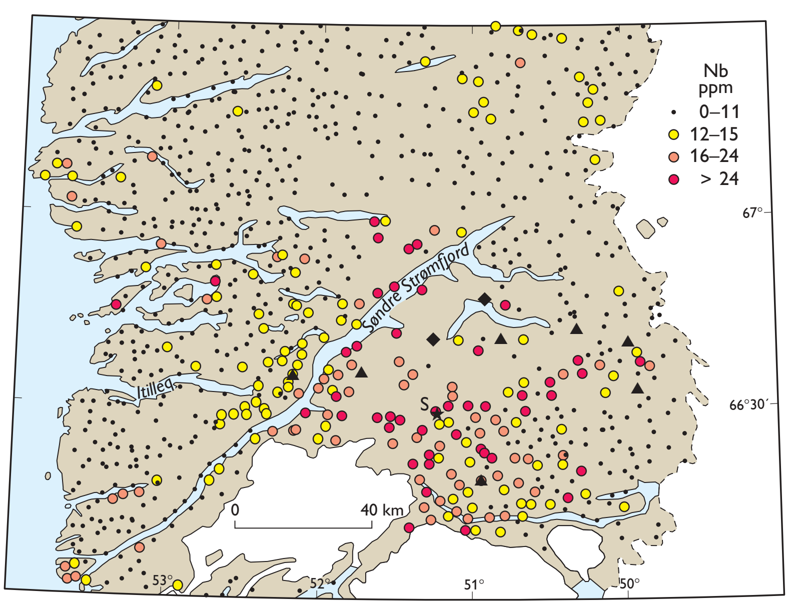

Fig. 4. Distribution of Nb in the < 0.1 mm fraction of stream sediments. **S**: Sarfartoq; **black triangles**: high-Mg, high-Cr chromite; **black diamonds**: high-Cr, low-Ca pyrope garnet.

contents of Nb. The regional stream sediment anomaly pattern for Nb in the study region (Fig. 4) does, in fact, coincide with the province of known kimberlites and lamproites.

It was recognised at an early stage that the Sarfartoq complex and surroundings were characterised by a regional stream sediment Nb anomaly (Steenfelt 1991). The anomaly was then attributed partly to Nb mineralisation, and partly to the known ultramafic alkaline dykes. As more stream sediment data became available (Steenfelt *et al.* 1993) and more kimberlite occurrences were registered, the apparent spatial relationship between the high Nb in stream sediments and occurrences of ultramafic alkaline dykes was strengthened.

Field visits to high-Nb stream sites were carried out in 2000 and 2001 to test the validity of high Nb in stream sediments as an indicator of kimberlite and lamproite. At one site with a very high Nb value a lamproite dyke was seen in outcrop in a stream gorge, and at other sites boulders of kimberlite were observed along the stream course. Outcrops or boulders of kimberlite or lamproite were not found in all the high-Nb sites visited. However, it is worthy of note that thin dykes and float of beforsite have been recorded some distance from the Sarfartoq carbonatite complex; beforsite is a magnesiocarbonatite rock with high concentrations of Nb and LREE, which probably contributes to the Nb-enriched province.

Stream sediment samples with high Nb and high-pressure chromite have been collected in areas east and south-east of known kimberlite occurrences suggesting a wider extent of the kimberlite field than recognised hitherto. A small cluster of high Nb values in the north-eastern part of Fig. 4 is at present unexplained. Kimberlites or lamproites have not so far been recorded here. However, the generally poor exposure in the stream surroundings would hinder ready recognition of alkaline dykes or other rocks with high Nb such as granitic pegmatites.

High concentrations of P, REE, Ba and Sr are recorded in stream sediment samples collected in a 15 × 15 km area near the coast south of Itilleq (locality I, Fig. 2). The geochemical signature of these samples is similar to that obtained in streams draining Palaeoproterozoic syenitic intrusives in the Nagssugtoqidian domain (Steenfelt 1998). It is noteworthy that the Nb concentrations are as low as in the Nagssugtoqidian syenites, and hence it was not expected to find kimberlites, but some other kind of alkaline rock.

Two field days were spent in a valley upstream from the most pronounced stream sediment anomaly. The area is dominated by a gneiss complex intruded by a 10 to 15 m wide Kangâmiut dyke and numerous thin, less than 0.5 m wide, dykes and sills of grey lamprophyre and a brown dolerite with star-shaped aggregates of phenocrystic plagioclase. Blocks of a coarse-grained alkaline ultramafic rock were frequently seen in the moraines of the valley glacier and were particularly abundant in the screes covering the southern valley slopes. The alkaline rock is dominated by black, shiny amphibole and has variable to large amounts of brown phlogopite and light green apatite. The finds explain the geochemical anomaly and enlarge the province of known alkaline rocks in this part of Greenland.

Mantle xenoliths in kimberlitic rocks

Mantle xenoliths are widely used in studies of the mantle lithosphere (Menzies & Hawkesworth 1987; Nixon 1987, 1995), and are here used to shed light on how the plate-tectonic history affected the deeper parts of the lithosphere across the Archaean–Proterozoic transition in the Sisimiut–Sarfartoq–Kangerlussuaq region. An extensive collection of xenoliths from several kimberlitic occurrences in the unreworked Archaean terrane south of Søndre Strømfjord was made in 2000, and two kimberlitic dykes containing abundant mantle xenoliths (localities A and B, Fig. 2) were visited and sampled in 2001. At least 90% of the xenoliths encountered have peridotitic or pyroxenitic compositions, and range in size from less than 1 cm to 15 cm across. Some xenoliths contain visible purple pyrope garnet (Fig. 5) and green Cr diopside, minerals that – given the right

Fig. 5. Kimberlitic dyke with many different types of mantle xenoliths (locality A, Fig. 2). Note purple garnets indicated with **arrows**; hammer and pencil for scale.

chemical composition – may indicate *P*–*T* conditions within the diamond stability field.

In the Palaeoproterozoic reworked Archaean terrane north of Søndre Strømfjord another kimberlitic dyke reported by exploration companies was visited (locality C, Fig. 2). The dyke consists of a 5–10 m wide, *c.* 500 m long train of kimberlitic boulders and outcrops in banded grey gneiss. Peridotitic and pyroxenitic xenoliths are abundant, ranging in size from less than 1 cm to around 10 cm. Dunitic (ol), harzburgitic (ol + opx) and lherzolitic (ol + opx + cpx ± gt) xenoliths were identified in the field. The Survey campaign located two further dykes north of Søndre Strømfjord (localities D and E, Fig. 2). The locality D dyke is vertical, 2–5 m wide and can be traced for *c.* 1.5 km. Xenoliths are much less abundant here than in the dykes south of Søndre Strømfjord, and their sizes range from less than 1 cm to about 5 cm. Macroscopically, the peridotitic xenolith types are dunite (ol) and lherzolite (ol + cpx + opx). The locality E dyke is a gently dipping (16–20°S), 30–50 cm thick sheet, and contains small xenoliths that are mostly less than 2 cm in diameter.

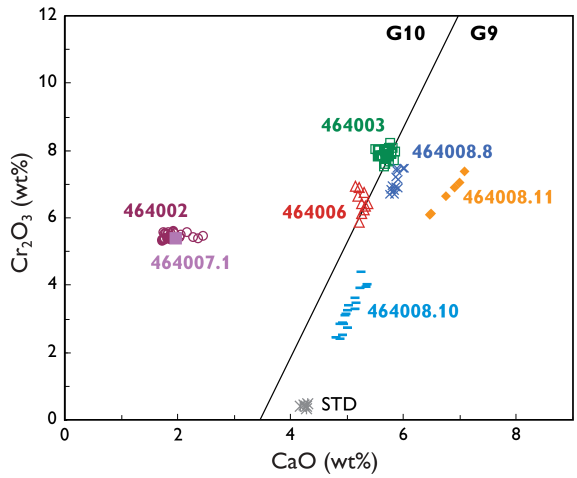

Fig. 6. Garnet compositions in xenoliths from the locality A dyke, analysed by electron microprobe. The **G9–G10** boundary line is from Gurney (1984) and Gurney & Zweistra (1995), and **STD** is a reference garnet analysed along with microprobe standards. GGU 464xxx numbers refer to sample material in the files of the Geological Survey of Denmark and Greenland.

Preliminary results

Seven xenoliths from the locality A dyke have been analysed for major element mineral chemistry by electron microprobe at the Geological Institute, University of Copenhagen, and garnets in three of them have been subjected to reconnaissance laser ablation analyses at the Survey. Garnets in the same three xenoliths were subjected to high-precision analysis of Ni by electron microprobe, and the xenolith rock types (Table 2) have been determined from their mineral assemblages and estimated mineral proportions (e.g. LeBas & Streckeisen 1991).

Generally, the major element compositions of minerals within individual xenoliths are homogeneous (Table 2). The average forsterite (Fo) content of the olivines ranges from Fo87 to Fo92; garnet wehrlites contain the olivines with the lowest Fo, garnet harzburgites and garnet lherzolites the olivines with the highest Fo. Average Ni contents are within the range of 2900 ± 360 ppm reported by Ryan *et al.* (1996) for garnet peridotites. Orthopyroxenes contain less than 1.6 wt% CaO and have relatively low Al_2O_3, the lowest values being from ilmenite-free garnet lherzolites (0.49–0.53 wt%). Clinopyroxene Mg/(Mg + Fe^{2+}) ratios correlate positively with Cr_2O_3. Garnet Mg/(Mg + Fe^{2+}) ratios tend to correlate positively with Fo contents of olivine. CaO and Cr_2O_3 contents of garnets show limited variation within individual xenoliths but large overall variations (Fig. 6), and the garnets from two harzburgite xenoliths clearly

Table 2. Calculated temperatures and pressures for xenolith minerals from the locality A dyke

Mineral analysed	GGU sample Rock type Minerals	464002.2 gt hzb ol-opx-gt	464003 gt lhz ol-opx-cpx-gt	464006 gt lhz ol-opx-cpx-gt	464008.10 gt lhz ol-opx-cpx-gt-ilm	464008.11 gt weh ol-cpx-gt
cpx	*T* (°C) *		1039 ± 30	1194 ± 30	1124 ± 30	1030 ± 30
cpx	*P* (kbar) *		48.9 ± 2.3	57.8 ± 2.3	68.7 ± 2.3	52.5 ± 2.3
gt	T_{Ni} (°C) †	1143 ± 42	1101 ± 18	1221 ± 30		

T, *P* and T_{Ni} calculated according to: * Nimis & Taylor (2000), † Ryan *et al.* (1996).
ol: olivine, opx: orthopyroxene, cpx: clinopyroxene, gt: garnet, ilm: ilmenite, hzb: harzburgite, lhz: lherzolite, weh: wehrlite.
The GGU numbers refer to material from Greenland in the files of the Geological Survey of Denmark and Greenland.

plot within the G10 field of Gurney (1984) and Gurney & Zweistra (1995). G10-class pyrope garnets are considered to be strongly indicative of conditions favourable for diamond stability.

Equilibration temperatures (*T*) and pressures (*P*) for the clinopyroxene-bearing xenoliths were calculated using the Nimis & Taylor (2000) single clinopyroxene thermobarometry equations (Table 2), and these temperature estimates are comparable to T_{Ni} values calculated using the high-precision Ni analyses and the empirical Ni-in-garnet thermometer of Ryan *et al.* (1996).

Variations of Zr vs. Y in garnets of three xenoliths from the locality A dyke are shown in Fig. 7, and averaged chondrite-normalised REE patterns for garnet and clinopyroxene in each xenolith in Fig. 8. The very low Zr and Y contents in garnets of a garnet harzburgite xenolith (sample GGU 464002.2) are consistent with their low-Ca character (Fig. 6) and indicate that this xenolith represents original lherzolite mantle depleted by partial melting (Griffin *et al.* 1992). The garnet in sample GGU 464002.2 is more depleted in the middle and heavy REE than the garnets in lherzolites from samples GGU 464003 and 464006. The sinuous pattern resembles that of low-Ca garnet in a harzburgite xenolith from the Sarfartoq area (Garrit 2000). The low REE contents support the idea that the garnet is hosted in a rock depleted by partial melting, whereas the sinuous shape may indicate post-depletion metasomatic enrichment processes (Hoal *et al.* 1984) or disequilibrium garnet growth (Shimizu & Sobolev 1995). Garnet lherzolites from samples GGU 464003 and 464006 have much higher Zr and Y concentrations in the garnets, and their chondrite-normalised REE patterns are more like those of typical LREE-depleted and MREE- to HREE-enriched garnets of primitive mantle (e.g. Haggerty 1995). Garnets from samples GGU 464003 and 464006 plot within fields indicating phlogopite and melt metasomatism of previously depleted mantle, respectively (Fig. 7). Phlogopite occurs in the xenoliths as part of kelyphitic rims on garnets, and in sample GGU 464003 also as a minor phase away from garnets. Ti contents of garnets, which follow Zr in some metasomatic processes (Griffin *et al.* 1999), show no significant zoning. This may indicate that if metasomatic processes affected garnet compositions, there was sufficient time for equilibration with the metasomatising agents.

Geophysical properties of kimberlites

Airborne geophysical surveys play an important role in diamond exploration, as kimberlites are often hidden under surficial deposits but also often have magnetic properties that make them distinguishable from the country rocks (e.g. Keating 1995; Macnae 1995). Since 1996 several helicopter-borne surveys have been commissioned by exploration companies to cover their licence areas in the Maniitsoq and Kangerlussuaq regions (Olsen *et al.* 1999). Data from the latest helicopter-borne survey in the Kangerlussuaq region in 2000 were used to outline targets for the drilling that led to the

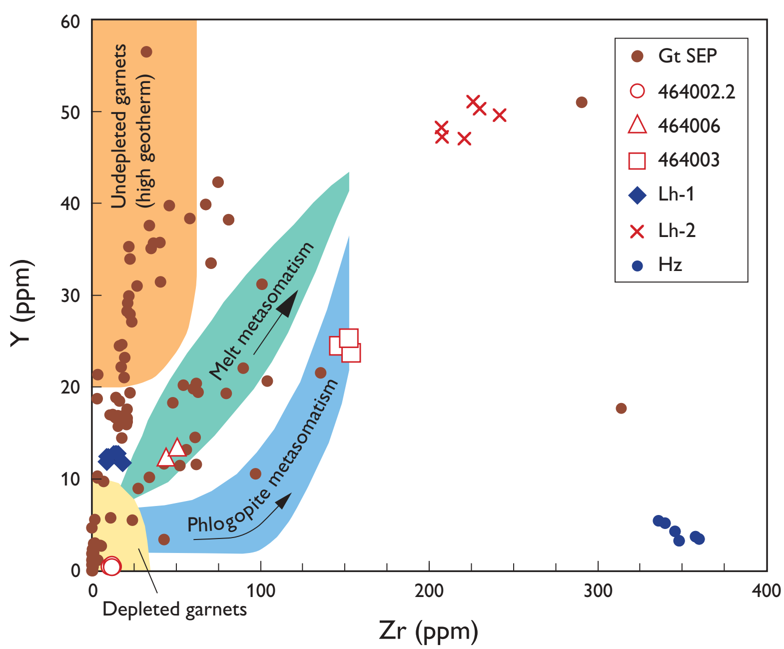

Fig. 7. Laser ablation ICP-MS analyses of Zr and Y in garnets from xenoliths in the locality A dyke (this study, data from GEUS), garnet lherzolite and garnet harzburgite xenoliths from the Sarfartoq area (Garrit 2000, data from Memorial University, Canada) and in garnet separates from the Sarfartoq area (**brown dots**: Garrit 2000, data from Macquarie University, Australia). The **coloured fields** are from Griffin & Ryan (1995) and Griffin *et al.* (1999), and **arrows** indicate core-to-rim zonation direction in metasomatised garnets of Griffin *et al.* (1999).

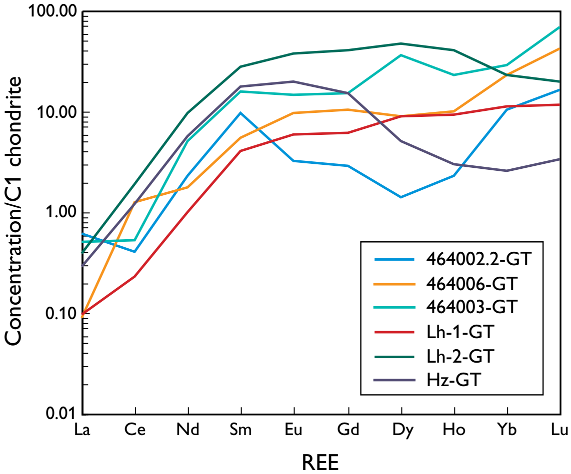

Fig. 8. Chondrite-normalised REE patterns of garnets in xenoliths from the locality A dyke (this study) and of garnets in Sarfartoq xenoliths (Garrit 2000). Laser ablation ICP-MS analyses, same sources as in Fig. 7.

confirmation of a 5 km long and 20 m wide kimberlitic dyke in late 2001 (locality J, Fig. 2; Fig. 9; Ferguson 2001).

The petrophysical properties of 22 representative kimberlitic samples collected in 2001 have been determined by the Geological Survey of Finland, and these data will be used in modelling the geophysical response obtained in the airborne surveys. It is planned to collect further samples for petrophysical measurements in 2002.

Conclusions and plans for further work

Field work in 2000 and 2001 in poorly known areas has added approximately 50 samples of kimberlitic dykes and more than 300 kimberlitic boulders to the existing databank.

Niobium in the fine fraction (< 0.1 mm) of stream sediments has proved to be a convincing 'pathfinder' element for kimberlites and lamproites in the Sisimiut–Sarfartoq–Kangerlussuaq region. Nb anomalies and the presence of high-pressure chromite in the stream sediment samples in the eastern and south-eastern part of the study area warrant follow-up.

The different xenolith types from the locality A dyke and their distinctive mineral compositions clearly demonstrate the heterogeneous character of the West Greenland lithospheric mantle, with a vertical zonation of depleted and metasomatised zones beneath the Archaean craton. Temperature and pressure calculations suggest that all xenoliths were derived from within the diamond stability field at a depth interval of 49–69 kbar, corresponding to approximately 150–215 km.

Although magnetic data have been used with some success in the search for kimberlitic dykes in the Kangerlussuaq region, there is a need for establishing a database with petrophysical properties of both kimberlitic dykes and host rocks in order to fully utilise the geophysical data available. Magnetic profiling at ground

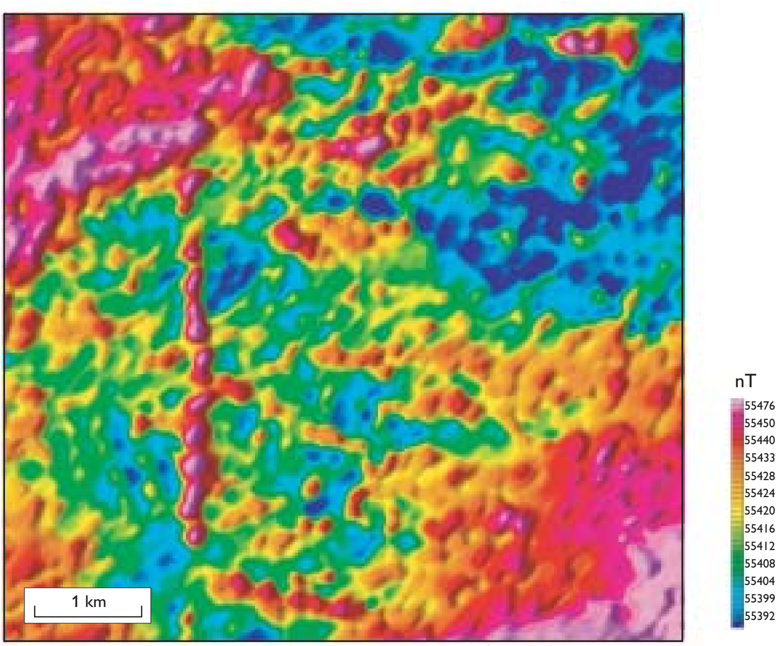

Fig. 9. Magnetic total field anomaly of locality J (Fig. 2), where a 5 km long and 20 m wide kimberlitic dyke shows up as pronounced linear feature. Data from helicopter-borne DIGHEM survey carried out for Dia Met Minerals Ltd., reproduced with permission.

level should be conducted at selected kimberlitic dyke occurrences in future field work.

Exploration companies have produced a large volume of data relevant to diamond exploration since 1995. The data include mineral analyses of heavy minerals recovered from till samples, dyke and boulder distribution maps, helicopter-borne geophysical surveys, results of diamond testing of mini-bulk sampled dykes, drill logs, etc. Compilation and publication of all non-confidential company data submitted in assessment reports to the Bureau of Minerals and Petroleum, Government of Greenland, is planned for 2002. A compilation of this type covering the North Slave Craton in Nunavut, Canada (Armstrong 2002) has received very positive response from industry.

The ultramafic alkaline rocks observed within the region north-west of the Sarfartoq cone sheet structure (Larsen 1980) have not been proved to be diamondiferous. However, the finds of diamonds in kimberlitic dykes of the Torngat orogen (Derbuch 2001) – the Canadian counterpart of the Nagssugtoqidian orogen – is an encouragement for further exploration in West Greenland.

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *smj@geus.dk*

Aeromagnetic survey in central West Greenland: project *Aeromag 2001*

Thorkild M. Rasmussen

The series of government-funded geophysical surveys in Greenland was continued during the spring and summer of 2001 with a regional aeromagnetic survey north of Uummannaq, project *Aeromag 2001* (Fig. 1). The survey added about 70 000 line kilometres of high-quality magnetic measurements to the existing database of modern airborne geophysical data from Greenland. This database includes both regional high-resolution aeromagnetic surveys and detailed surveys with combined electromagnetic and magnetic airborne measurements.

High-quality magnetic data are now available for all the ice-free area of West and South Greenland from the southern tip of Greenland to Upernavik Kujalleq/Søndre Upernavik (Fig. 1). The total surveyed area with high-resolution magnetic data is 250 000 km^2 and corresponds to a total of 515 000 line kilometres. Detailed surveys with combined electromagnetic and magnetic measurements were carried out in six separate surveys in selected areas of high mineral potential during project *AEM Greenland 1994–1998*, a total of 75 000 line kilometres. Descriptions of the previous surveys can be found in Thorning (1993), Stemp & Thorning (1995), Thorning & Stemp (1996, 1998), Stemp (1997), Rasmussen & Thorning (1999), Rasmussen & van Gool (2000) and Rasmussen *et al.* (2001).

The primary objective of the government-funded airborne geophysical programme is to provide the industry and the geoscientific community with modern data that are relevant to the exploration for mineral resources and for the general understanding of the geology of Greenland. Most of the previous surveys have covered onshore areas. However, the survey in 2001, like the survey in 1997 in the Disko Bugt region, also included significant offshore areas. Approximately one third of the 2001 survey region is offshore, and includes an area well known for its hydrocarbon potential (Christiansen *et al.* 1995, 2000).

The *Aeromag 2001* survey block in central West Greenland extends between latitudes 70°30´ and 72°12´N, covering the entire ice-free land area together with a part of the offshore area and the border of the Inland Ice (Figs 1, 2). The 2001 survey was flown for the Bureau of Minerals and Petroleum, Government of Greenland by Sander Geophysics Ltd, Ottawa from late May to mid-September. The project was supervised and managed by the Geological Survey of Denmark and Greenland (GEUS).

The field operation was based at Qaarsut airport as was the magnetic base station utilised for correction of magnetic diurnal variations. Details of the survey operation and equipment can be found in a report by Sander Geophysics Ltd (2002).

Products

The survey was carried out by flying along a gently draped surface 300 m above the ground and sea level. Survey lines were aligned in a N–S direction with a separation of 500 m. Orthogonal tie-lines were flown with a separation of 5000 m. Total magnetic field data were recorded with a sampling rate of 0.1 sec which corresponds to a sampling distance of 7 m. The magnetic field at the base station was recorded with a 0.5 sec sampling rate. Aircraft positional data from GPS (Global Positioning System) measurements were recorded with a 1 sec sampling rate, and aircraft altitude measurements obtained from barometric altimeter and radar were recorded with a sampling rate of 0.25 sec. A continuous video-tape record of the terrain passing below the aircraft was made.

In addition to the line data obtained from the measurements, maps at scales 1:250 000 and 1:50 000 have been produced by interpolation and gridding of the measured data. Vertical gradient data of the magnetic total field were calculated from the gridded magnetic total field data. Altogether five new maps (magnetic total field intensity, associated vertical gradient, shadow of the total magnetic intensity, combined shadow and colour of magnetic total field intensity and topography) at scale 1:250 000 of the entire survey area and three sets of maps (colour and contours of magnetic total

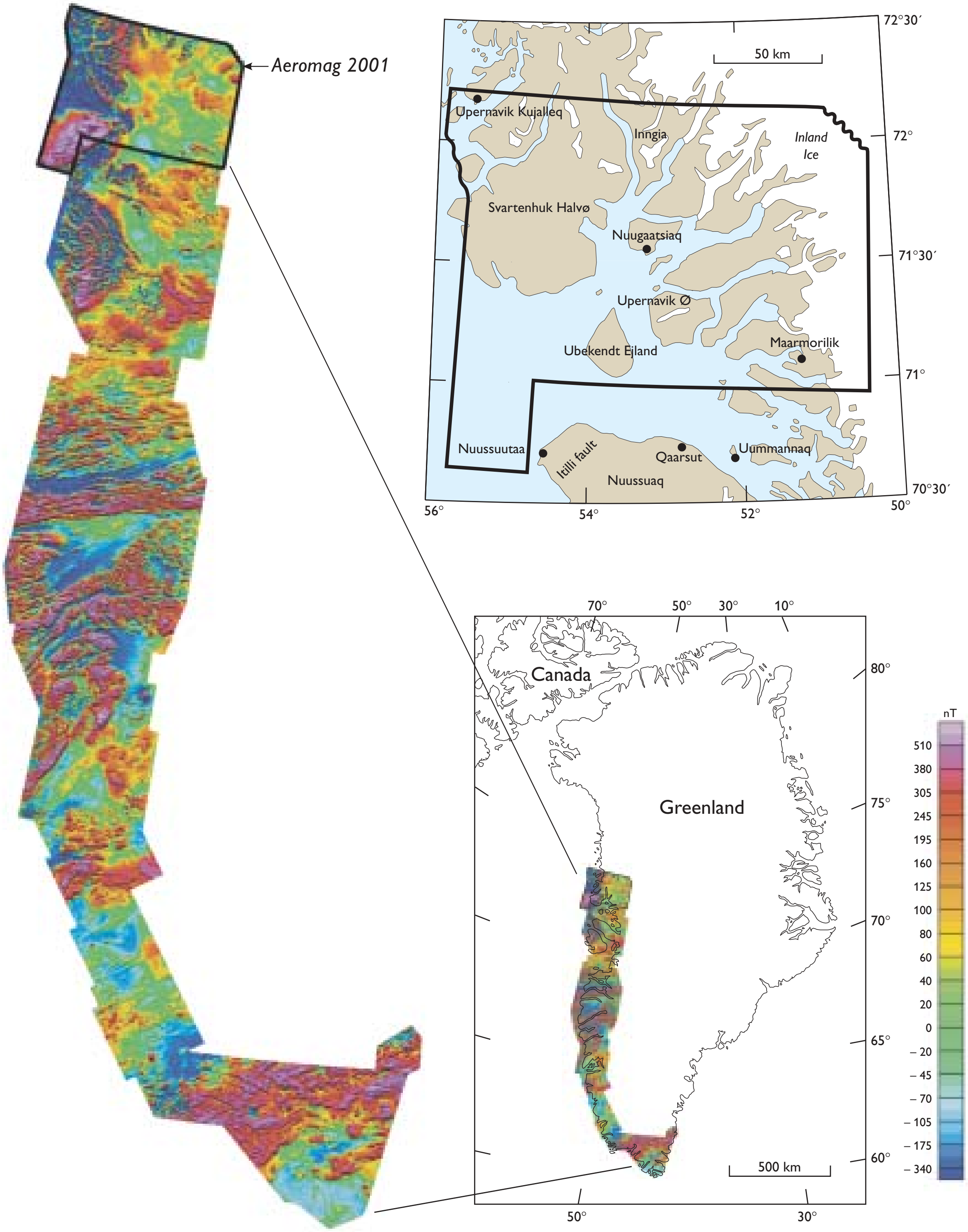

Fig. 1. Coverage of government-financed aeromagnetic surveys in western Greenland during the period 1992–2001. The location of the aeromagnetic survey in 2001 is circumscribed by a **black line**.

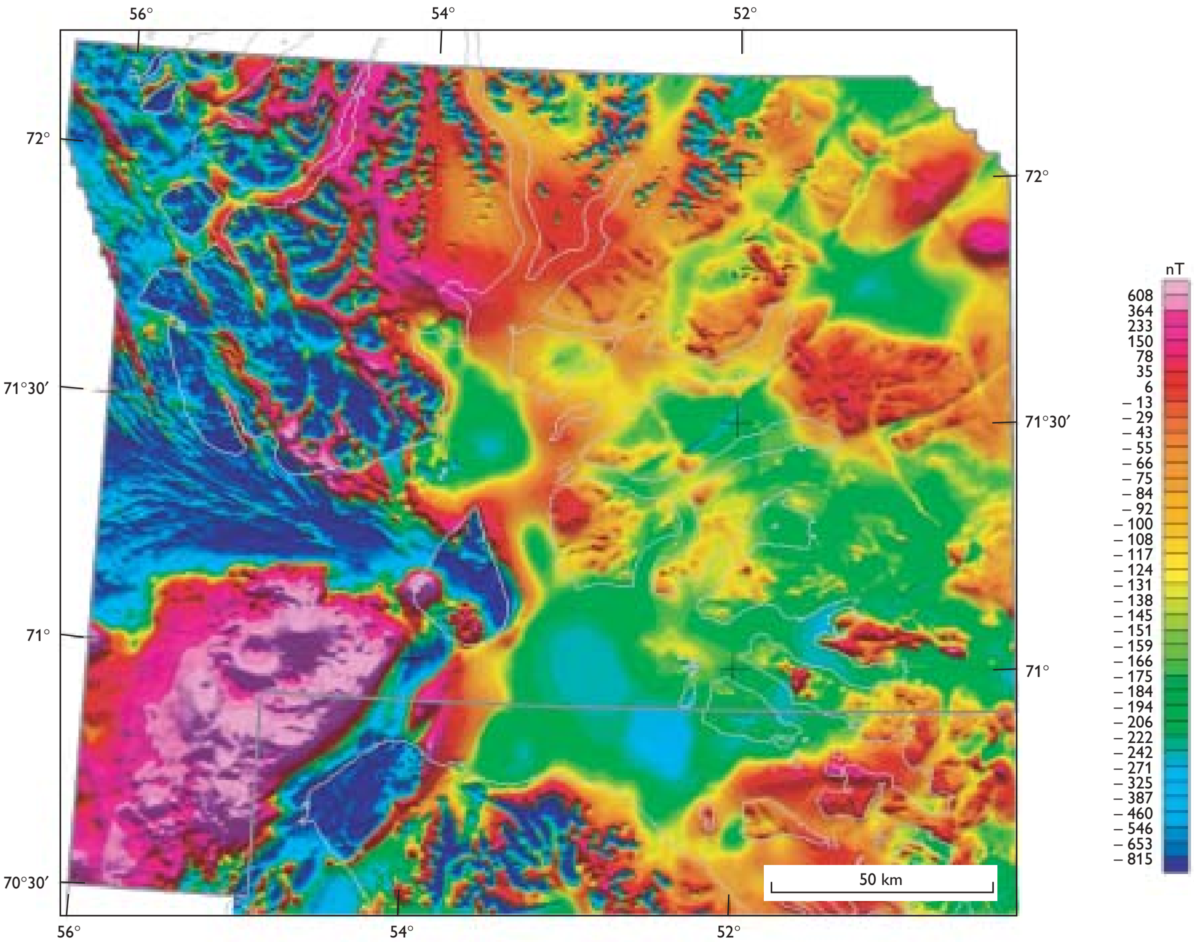

Fig. 2. Magnetic total field intensity with shaded relief for the area in central West Greenland covered by project *Aeromag 2001*. The location of the aeromagnetic survey in 2001 is circumscribed by a **grey line** and the new data have been merged with data from project *Aeromag 1997*.

field intensity and flight path) each comprising 32 sheets at scale 1:50 000 are included in the map series.

The gridded magnetic total field data from *Aeromag 2001* are shown in Fig. 2. The data have been merged with those from the *Aeromag 1997* project. The International Geomagnetic Reference Field corresponding to the date of measurement has been subtracted from the data. Shaded relief data, superimposed on the magnetic total field data, have been modelled by using a light-source illumination from north with an inclination of 45°. The magnetic anomalies are in the range from –2500 to 2000 nT. The calculated vertical gradient of the magnetic total field is shown in Fig. 3 for the merged data set. Some implications of the new geophysical data for the interpretation of the geology are given below after a short introduction to the geology.

Geology of the surveyed area

Five geological maps at scale 1:100 000 have been published of the surveyed area by the Survey; a descriptive text for three of the map sheets is given by Henderson & Pulvertaft (1987). The surveyed area between Uummannaq and Upernavik Kujalleq/Søndre Upernavik comprises Archaean crystalline basement rocks overlain by a several kilometres thick succession of Palaeoproterozoic supracrustal rocks; they are intruded by a Palaeoproterozoic granitic complex. Minor units of down-faulted Cretaceous sediments occur, and Palaeogene plateau basalts are prominent onshore and offshore. The Precambrian rocks have been correlated with similar rocks on Baffin Island in Canada, and were folded and metamorphosed during the Hudsonian

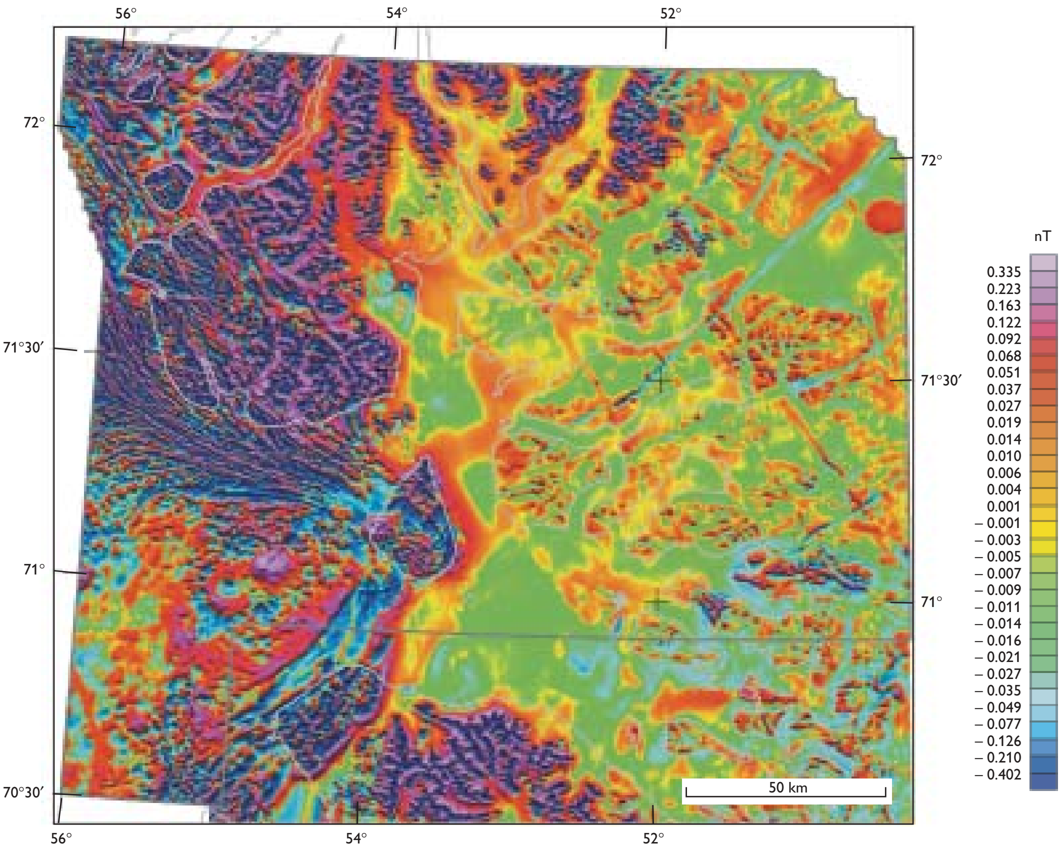

Fig. 3. Calculated vertical gradient of the total magnetic field intensity with shaded relief for the area in central West Greenland covered by project *Aeromag 2001*. The location of the aeromagnetic survey in 2001 is circumscribed by a **grey line** and the new data have been merged with data from project *Aeromag 1997*.

orogeny at around 1.85 Ga, and intruded by a 1.65 Ga old swarm of dolerite dykes.

The Palaeoproterozoic metasediments (the Karrat Group) host the now exhausted Black Angel Pb-Zn ore bodies (13.5 mill. tonnes ore at 4.0% Pb and 12.3% Zn) which were mined from 1973–1990. Similar marble-hosted lead-zinc occurrences at other localities indicate an additional potential for this type of mineralisation. The clastic facies of the Karrat Group include extensive sulphide facies iron formation and vein-type base and precious metals mineralisation, and offer a potential for shale-hosted massive sulphides and turbidite-hosted gold-bearing veins and shear zones (Thomassen 1992).

The Karrat Group crops out within the Rinkian Belt of central West Greenland, a region that is characterised by gneiss domes and fold nappes with sheath-like geometry and flat-lying axial surfaces that affect both Archaean basement gneisses and the Palaeoproterozoic Karrat Group. Grocott & Pulvertaft (1990) identified seven phases in the tectonic evolution of the region, of which three involve extension and four compression.

The southern and south-western part of the surveyed region preserves extensive areas of Palaeogene volcanic rocks, related to the plate break-up between Greenland and Baffin Island. These volcanic rocks represent, together with similar volcanic rocks on the Canadian side of Davis Strait and on the east coast of Greenland, the results of mantle plume activity along the track of the present Iceland mantle plume (Storey *et al.* 1998). In the surveyed area volcanic activity started in mid-Paleocene time with deposition of the Vaigat Formation. The earliest volcanics were extruded below sea level as hyaloclastite breccias, while most later volcanism was subaerial. The Vaigat Formation is dominated by picritic and other olivine-rich tholeiitic basalts; it is between 0 and 3 km thick on Svartenhuk Halvø and more than 5 km thick on Ubekendt Ejland (Hald & Pedersen 1975). In the northern part of the basalt-covered area, the Vaigat Formation was followed by deposition of about 50 m of fluvio-lacustrine sediments and hyaloclastite breccias. The succeeding volcanic rocks of the Svartenhuk Formation are characterised by plagioclase-porphyritic and aphyric basalts, and have a minimum thickness of 2.8 km. Determinations of the magnetic palaeodirection and palaeointensity from samples of the Vaigat Formation at Nuussuutaa on Nuussuaq have been presented by Riisager & Abrahamsen (1999) and Riisager *et al.* (1999). The lower part of the Vaigat Formation (the Anaanaa Member and part of the Naujánguit Member) has normal magnetisation (C27N), whereas the upper part of the Vaigat Formation is reversely magnetised. Palaeomagnetic data for the Maligât Formation on Nuussuaq, a stratigraphic equivalent to the Svartenhuk Formation, yielded reverse magnetisation directions; a detailed chronostratigraphy has not yet been established. The Palaeogene volcanics are characterised by units of strongly reduced lavas with native iron, indicating a potential for Norilsk-type nickel-copper-PGM in the plateau basalt areas.

Magnetic anomaly maps and geological implications

The geophysical data illustrated in Figs 2 and 3 are considerably simplified representations of the original data sets, but major anomalies can be discerned. Onshore, six sub-parallel linear anomalies striking NNW–SSE cross the entire survey area. Some of these coincide with the locations of mapped Mesoproterozoic mafic dykes of the Melville Bugt dyke swarm (Nielsen 1987). The dolerite dykes and thin layers of hornblende schist and amphibolite at many inland locations (Henderson & Pulvertaft 1987) are seen very clearly in the magnetic response.

Elongated anomalies with variable strikes between 40–65° and with distinct minimum magnetic total field values are visible in the eastern half of Figs 2 and 3. These structures, many in areas covered by ice, appear not to have been deformed, which implies that they are younger than the Rinkian orogeny. Of the five anomalies of this type, the most prominent is a NE–SW feature with its south-western termination at Upernivik Ø. This anomaly may be an extension of the Itilli fault that crosses the westernmost part of Nuussuaq, and is marked by a sharp transition between positive and negative magnetic total field anomaly values. However, none of these anomalies have so far been correlated with any confidence with known geological structures. The amplitudes of the anomalies are in the order of –150 nT and may have a magnetisation direction opposite to the present geomagnetic field direction.

The Palaeogene basalts dominate the magnetic response in the coastal region and the offshore part of the survey. Differences in polarities of the basalts are clearly defined by the low magnetic field values on Svartenhuk Halvø and the positive values west of Nuussuaq. On Ubekendt Ejland both the acid tuff/ignimbrite mapped on the western part of the island and the granite intrusion on the southern part are associated with positive magnetic anomalies.

A distinct pattern of elongated, arcuate anomalies is dominated by low magnetic values. A similar anomaly pattern is not visible in the area with high magnetic field values. Comparison with mapped faults and dykes on Svartenhuk Halvø (Larsen & Pulvertaft 2000) shows an excellent correlation between the magnetic lineaments and geologically mapped structures, e.g. dykes and presumed non-exposed dykes associated with faults. However, basalt with normal magnetisation at depth in conjunction with vertical displacement along faults may also contribute to the anomalies. Topographic effects clearly contribute to the anomaly pattern, but are not sufficient to explain the anomalies. The distinct differences in anomaly pattern between areas with positive and negative magnetic anomaly values may be a result of difference in: (1) rheology due to difference in thermal state and pressure at the time of magmatic activity; (2) crustal composition; (3) volcanic source type. Firstly, the time span between the eruption of two different magma types may have been sufficiently long that the thermal state and pressure in the crust may have changed, leading to a difference in eruption style and in the amount of dyke intrusion. Secondly, the initial composition of the crust at the location of the magnetic high may have been unfavourable for the creation of faults and intrusion of dykes. Thirdly, the basalt region with reverse magnetisation may be an amalgamation of lavas from numerous eruptions with limited flow distances whereas the basalt with normal magnetisation may represent episodes with flows of a much larger extent. The magnetic data alone are not conclusive with respect to which of the three interpretations are correct. Establishment of age relationships between the two types of basalts is essential for a reliable interpretation. In particular, if the basalt of the area with high magnetic field values was extruded after the basalt causing low magnetic values, a mechanism must be found that explains why none of the elongated anomalies within the area of low magnetic intensity are truncated by basalts with normal magnetisation.

Conclusions

The aeromagnetic survey has revealed a number of regional anomalies that must be accounted for when interpreting the geology of the region. Some of the major structures seen on the map of the magnetic total field intensity do not correlate with geologically mapped structures, and further geological and geophysical mapping, offshore as well as onshore, is necessary in order to gain more insights into the structural development of the area.

This paper has focused mainly on anomalies of regional extent. Many local anomalies can be identified, but interpretation requires a thorough modelling of topographic effects. A discussion of these anomalies and their implications for mineral prospecting in the region will be presented elsewhere.

Acknowledgements

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Author's address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *tmr@geus.dk*

Tsunami-generating rock fall and landslide on the south coast of Nuussuaq, central West Greenland

Stig A. Schack Pedersen, Lotte Melchior Larsen, Trine Dahl-Jensen, Hans F. Jepsen, Gunver Krarup Pedersen, Tove Nielsen, Asger Ken Pedersen, Frants von Platen-Hallermund and Willy Weng

During the afternoon of 21 November 2000 the village of Saqqaq in central West Greenland was hit by a series of giant waves. Ten small boats were destroyed, but luckily neither humans nor dogs were killed. The following day a police inspection by helicopter revealed that the giant waves were caused by a major landslide at Paatuut, *c.* 40 km north-west of Saqqaq on the south coast of Nuussuaq (Figs 1, 2). The landslide deposits were dark grey-brown in colour, in marked contrast to the snow-covered slopes, and protruded as a lobe into the Vaigat strait. Along the adjacent coastlines the snow had been washed off up to altitudes about 50 m a.s.l. and severe damage had been caused at the abandoned coal-mining town Qullissat on the opposite side of Vaigat.

Landslides in Greenland

Landslides in Greenland are influenced by permafrost, glacial ice, high topographic relief and repeated freezing and thawing (Pedersen *et al.* 1989). In most parts of Greenland where gneisses and granites dominate, slides are rare. By contrast, the Nuussuaq Basin comprises weakly consolidated sedimentary rocks overlain by a thick pile of dense volcanic rocks. This stratigraphical succession is favourable to the generation of slides. Consequently, large parts of Disko, Nuussuaq and Svartenhuk Halvø are strongly affected by landslides, especially along the coasts (Fig. 2).

Tsunamis

In coastal areas landslides may reach the sea and generate swells which may travel considerable distances. The swells present a much larger risk than do the landslides because they affect much larger areas. A wave (swell) may not be noticeable in open waters off the coast, but grows rapidly as it approaches the shore. Swells of this type are known as tsunamis and are frequently generated by submarine earthquakes. The giant waves which hit Saqqaq, Qullissat and the shores of the Vaigat in November 2000, are referred to below as a tsunami, although they were initiated by a landslide.

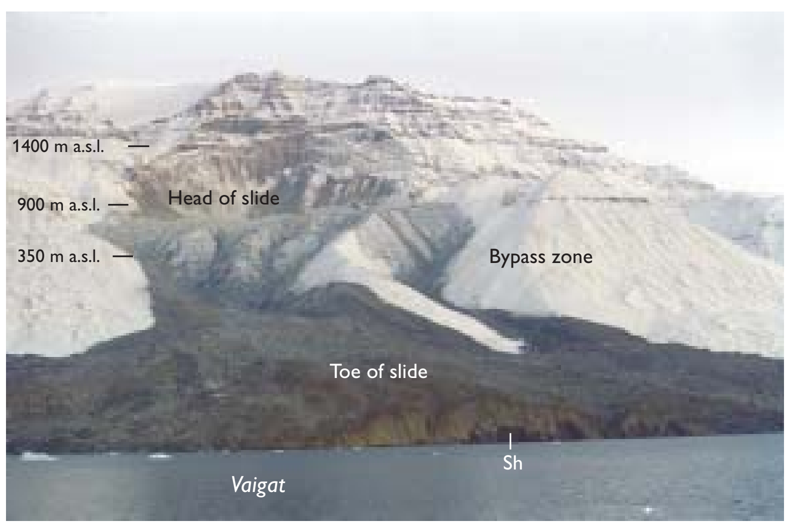
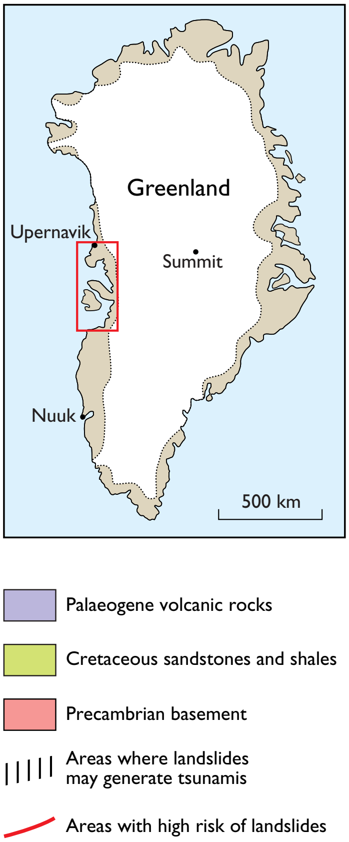


Fig. 1. The 21 November 2000 landslide at Paatuut, viewed from the sea a few days later. The slide lacks snow cover; cf. Fig. 4. Note the black shale (**Sh**) cropping out in the lower part of the coastal escarpment. Photo: Christoffer Schander, Arktisk Station, Qeqertarsuaq.



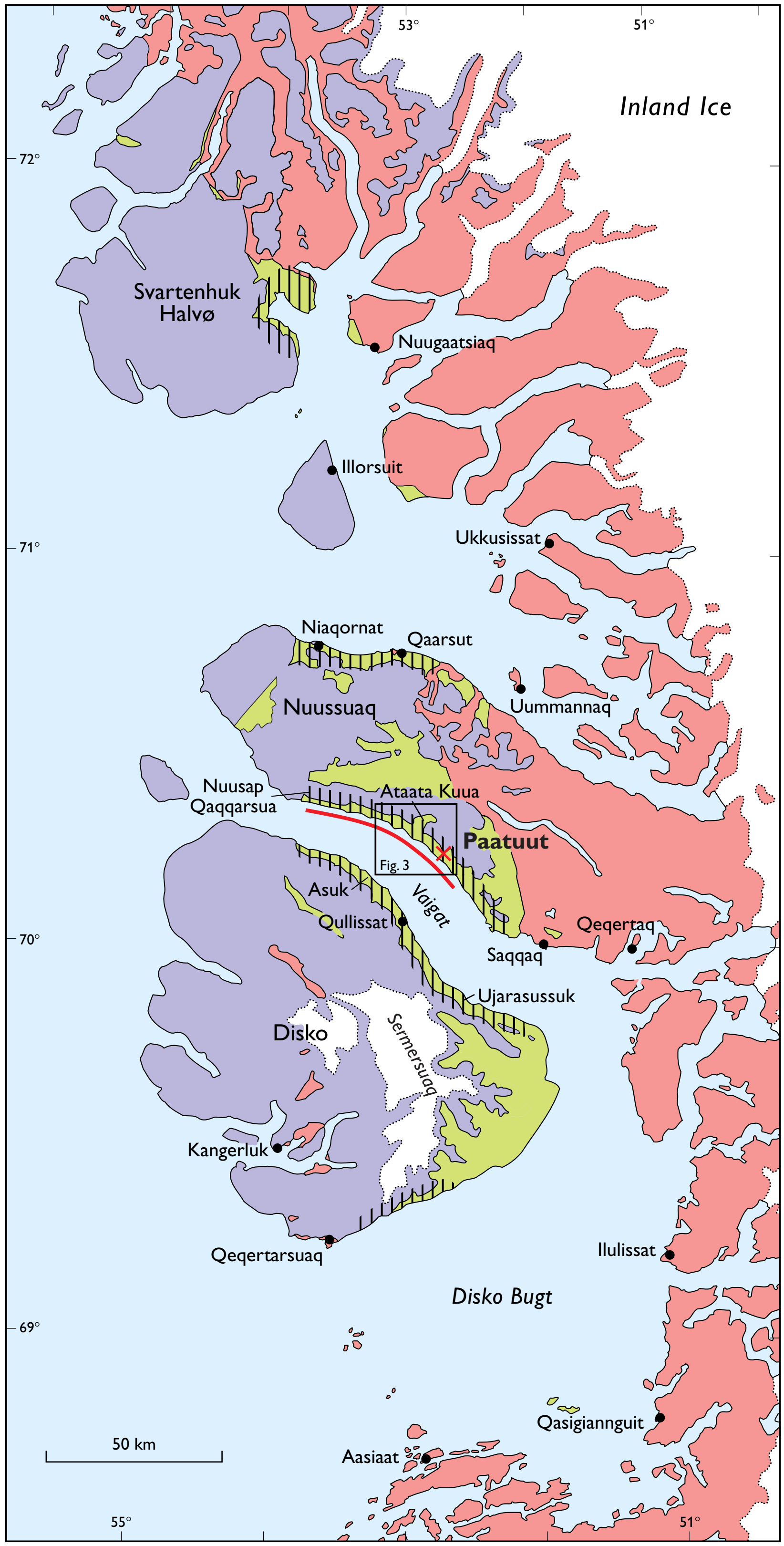


Fig. 2. Geological map of the Nuussuaq Basin with the landslide-prone areas indicated. Frame shows location of Fig. 3, a detailed map of the Paatuut area.

Landslides may move at different speeds, and slowly moving slides or debris flows are not considered dangerous. To initiate a tsunami the landslide must almost instantly displace huge volumes of water, and the likelihood of such an event increases with the steepness of the coast. The risk of tsunamis following landslides is consequently particularly high along the steep south coast of Nuussuaq where erosion is rapid and large volumes of debris accumulate at high altitudes (Fig. 2). Furthermore, tsunamis generated along the south coast of Nuussuaq are confined by the narrow Vaigat strait and are reflected from the opposite coast.

Rock falls and landslides in the Disko–Nuussuaq area

Old slide areas are recognisable from their geomorphological expression, and sometimes also by brick-red colours produced by self-combustion in slipped carbon-rich shales. Such burnt lithologies are prominent at Paatuut and Ataata Kuua (Fig. 3) and indicate a high frequency of slides. Many slides are indicated on the Survey's 1:100 000 geological maps of the region. Most of these slides must be less than 10 000 years old, as they post-date the last glaciation. In the period 10 000–3000 B.P. relative sea level was falling in the Disko Bugt area, and marine terraces as well as raised beaches were formed. Since 2800 B.P. sea level has been rising (Long *et al.* 1999). Along that part of the south coast of Nuussuaq where landslides are frequent, marine terraces are generally not seen; this indicates that the landslides present are probably younger than 3000 B.P.

The Paatuut area is characterised by large landslides (Fig. 3). Between Paatuut and Ataata Kuua in particular, large lobes of rock debris superpose the glacial morphological surface. Huge solitary blocks of volcanic rocks on the slopes facing Vaigat are evidence of occasional rock falls, some of which may have generated tsunamis.

The first published account of a landslide in Greenland is that of Steenstrup (1900), who recorded an event that occurred in 1870 near Ujarasussuk on the north coast of Disko. A mudflow with large floating blocks of basalt built a lobe into the sea and hindered passage on foot along the coast. This landslide does not appear to have caused a tsunami or any damage to houses or inhabitants in Ujarasussuk.

Landslides are a recurring phenomenon near Niaqornat in northern Nuussuaq. In most cases spontaneous combustion in shales is reported about one year after the slide (Rosenkrantz 1967; Henderson 1969). The village Niaqornat was hit by falling rocks in 1978, and west of the village the risk of future slides is high (Pulvertaft 1979).

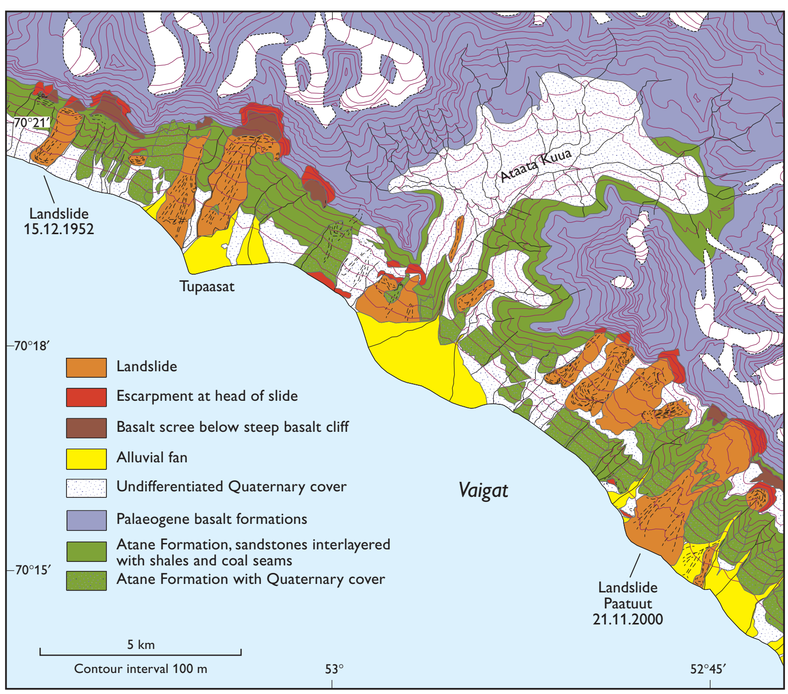


Fig. 3. Map of part of the south coast of Nuussuaq showing the many large and small landslides in the area, including the new slide at Paatuut. The contours are drawn from vertical aerial photographs at scale 1:150 000 taken in 1985 and, for the Paatuut slide, from oblique photographs taken in July 2001.

On the south coast of Nuussuaq, west of Tupaasat (Fig. 3), a large landslide occurred on 15 December 1952. The slide was initiated 700 m a.s.l. and had a width of 1 km where it reached the sea. It generated a tsunami which caused some damage in Qullissat; areas 50–100 m from the shoreline were flooded, the electricity plant was damaged and a boat (22 ft cutter) with a crew of three was washed ashore with the loss of one man.

In the period 1984–1988 a mudflow at Paatuut was active. Black shales derived from an altitude of 800 m constituted the bulk of the flow. This section of the coast appears to have been affected by a number of flows ranging from dilute mudflows building alluvial fans to denser mudflows. The last of these occurred in 1997 and is not reported to have generated a tsunami.

Evidence from geophysical investigations

The Vaigat strait is up to 650 m deep with a U-shaped cross-section. This is interpreted as the result of erosion during the Pleistocene by the Vaigat Ice Stream, which drained from the Inland Ice into the Davis Strait. During the summer of 2000, the Survey acquired a large number of reflection seismic profiles in Vaigat with a 600 m streamer and 40 l airgun array (Marcussen *et al.* 2001). In the seismic profiles a number of chaotic local accumulations of sediment are apparent, which are interpreted to be old submarine slides or subaqueous aggradations from subaerial landslides. The thickness of such slide-deposited sediments is generally 50–100 m, but may locally exceed 200 m. The data do not allow a distinction between sediments deposited by a single slide and the composite accumulations formed by numerous slides.

The 21 November 2000 landslide

Stratigraphy

The stratigraphic succession at Paatuut comprises siliciclastic sediments of the Cretaceous Atane Formation and the Danian Quikavsak Formation, overlain by hyaloclastite breccias and subaerial lava flows of the Paleocene Vaigat and Maligât Formations (Pedersen & Pulvertaft 1992; Pedersen *et al.* 1993; Dam & Sønderholm 1998; Dam & Nøhr-Hansen 2001).

The Atane Formation is exposed up to altitudes of 800 m. Lithologies consist of white to yellow, weakly consolidated 1–10 m thick sandstones interbedded with dark grey, 2–15 m thick shales and coal seams typically 0.5–1 m thick. In places the coal seams have undergone self-combustion after landslides, and the black shales are converted into brick-red, orange or pink tiles. The Quikavsak Formation constitutes palaeovalley fill and is exposed locally at altitudes of 400–900 m. It consists of whitish pebbly sand overlain by black mudstones. The mudstone level around 900 m a.s.l. corresponds to the level above which material was removed during the landslide. This level is clearly seen in the post-slide terrain model (see below).

The lowest volcanic rocks are 260 m thick hyaloclastite breccias of the Ordlingassoq Member of the Vaigat Formation. At altitudes of 1160–1450 m these are overlain by thin, greyish picritic subaerial lava flows of the same member. The volcanic rocks above 1450 m a.s.l. are brownish subaerial lava flows of the Maligât Formation. Dykes and up to 20 m thick sills cut the succession, and the sills often form prominent ledges on the sandstone slopes. Blocks of all the volcanic and intrusive lithologies have been recognised amongst the material in the landslide.

Slide morphology

The morphology and main features of the landslide can be clearly seen in the photographs of Figs 1 and 4, taken respectively a few days after the event and in July 2001. The slide was initiated at altitudes of 1000–1400 m a.s.l., referred to as the head of the slide (Fig. 1). The material transported by the slide comprises partly blocks of basalt that formed a steep scree prior to the slide, and partly solid slabs of basalt broken off from the cliff.

The central part of the slide is a series of gullies and ridges in the Atane Formation; the material was transported downwards through these pre-existing gullies. They were not deepened significantly due to erosion during the slide, and this area is classified as a bypass zone.

The lower part of the slide is a lobate accumulation of material deposited on the former alluvial fan at the base of the slope (Fig. 4). This aggradational toe of the landslide has a width of *c.* 2 km and is bounded seawards by a coastal escarpment (Fig. 4). The research vessel *Porsild* collected a number of echo sounder profiles off the coast of Paatuut in July 2001. These data provide the first approach to a detailed map of the sea floor (Pedersen *et al.* 2001, fig. 29) and reveal a rapid increase in water depth and very uneven sea-floor topography. Earlier seismic investigations have also

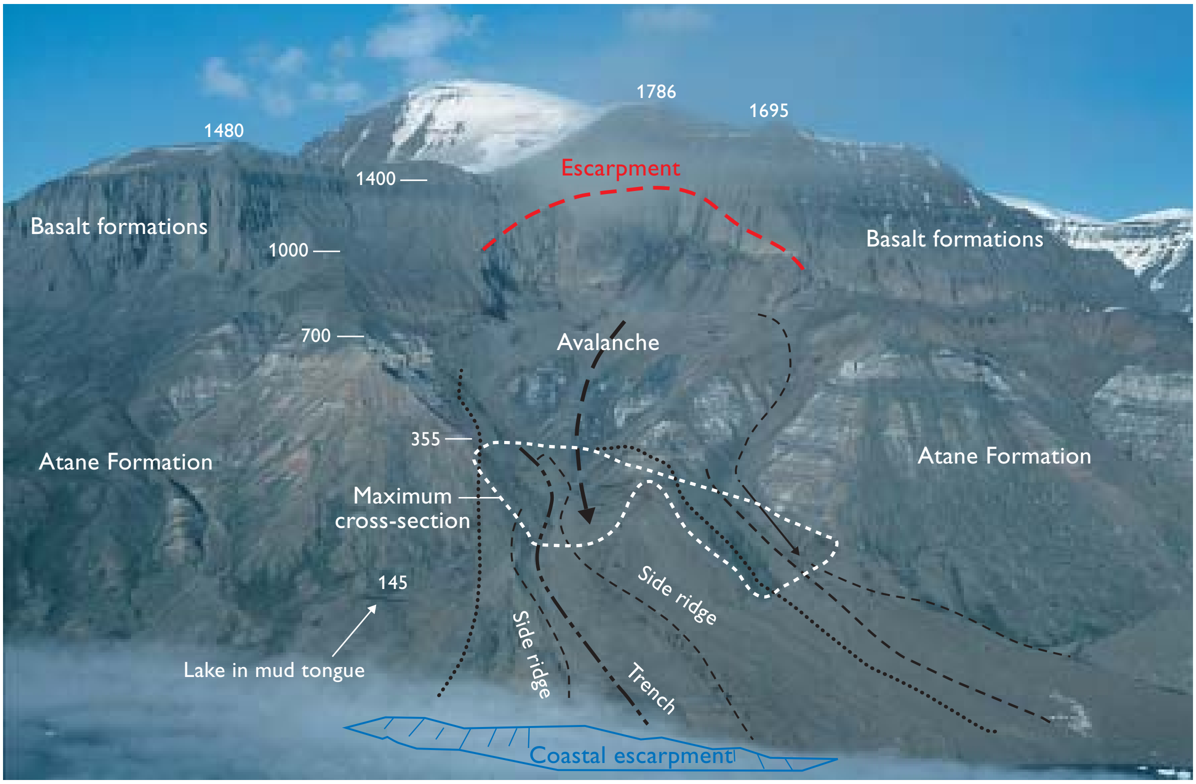


Fig. 4. Oblique photograph of the Paatuut landslide taken in July 2001 from a helicopter. The photograph was used in the multi-model photogrammetric work; low-lying areas are concealed by coastal fog. The direction of main flow in the bypass zone is indicated by an **arrow**, and the cross-section of the avalanche at its maximum is marked by a **dotted contour**. Some ridges and trenches in the toe of the slide are indicated. The light, smeared patch above the escarpment is a dust cloud raised by continuing small rock falls from the back wall. Elevations are in m a.s.l.

documented an uneven topography offshore Paatuut (Marcussen *et al.* 2001), which is believed to reflect the distribution of a succession of submarine slides.

Head of slide (denudation zone)

The slide escarpment along which material slipped and slid bounds the head of the slide (Figs 1, 4). The escarpment comprises two steep (*c.* 60°) surfaces, which meet at a high angle. Along the eastern escarpment surface the slip was down-dip, and the vertical offset seen on the denudated surfaces ranges from 121 m to 182 m; this surface is interpreted as a pre-existing fault plane, and the newly exposed rock has a pale colour (Fig. 4). The western surface constitutes a side escarpment which was clearly affected by oblique lateral movement during the landslide event, as indicated by groove mark striation on the cliff. Based on the disrupted character of the landslide material and the steepness of the slide escarpment, the process at the head of the slide is interpreted as a rock fall.

A platform at an altitude of 800–900 m occurs at the base of the escarpment. Prior to the landslide this platform was characterised by accumulation of glacial deposits. The platform may mark the boundary between the shaly lithologies and the sandstones of the Quikavsak Formation and the hyaloclastite breccias of the Ordlingassoq Member. After the slide, the platform appears as a barren landscape characterised by huge blocks and chaotic disrupted material on which frost mounds have subsequently developed (Pedersen *et al.* 2001).

Central part of slide (bypass zone)

The central part of the slide is a bypass zone where the slide material was transported through the gullies in the Atane Formation. The gradient in the gullies varies

Fig. 5. Blocks and boulders in the central part of the toe of the Paatuut landslide are interpreted as grain flow deposits. **Arrow** indicates person for scale. Photograph taken July 2001.

from 26° to 36°. Field work in 2001 showed that some slide material was deposited about 200 m above the floor of the gullies during transport through the bypass zone. Groove marks with a gentle plunge towards the coast were observed on the sides of the gullies. A minor quantity of white sandstones of the Atane Formation was removed from the top of a gully and deposited in a separate lobe in the aggradation zone (lower right corner of Fig. 4). This suggests that the transport and deposition of the sandstones occurred as a discrete event during a late phase of the slide.

The drape of mud, stones and boulders on the sides of the gullies outlines the space taken up by the flow. The maximum cross-sectional area through which the avalanche passed is calculated to 70 000 m^2. Seismic data (see below) show that the main event lasted for approximately 80 seconds; however, the maximum cross-section would only have been sustained during a considerably shorter period. This gives a *minimum* velocity of the slide through the bypass zone of 60 km/h, indicating that in the bypass zone the landslide had the character of a rock avalanche. The seismic data give considerably higher average velocities.

Toe of slide (aggradation zone)

Morphologically the lower part of the slide comprises two lobes which merge downwards into one, with a surface lined by trenches, ridges and flats (Figs 4, 5). The floors of the trenches may be as much as 50 m below the crests of the ridges. The alluvial fan upon which the landslide was deposited had a dip of 6°–9°, and the aggradation is up to 60 m (see later). The ridges consist of clast-supported, apparently matrix-free conglomerates and are interpreted as grain flow deposits. The flats consist of clast-supported, matrix-bearing conglomerates and matrix-supported conglomerates, indicating deposition from modified grain flows and debris flows. In the flat areas frost mounds are common, indicating the presence of fine-grained sediment at the base of the deposit.

On the western side of the landslide a tongue of mud extends away from the main slide. Field observations (Pedersen *et al.* 2001) indicate that this tongue formed due to gravity spreading of the avalanche as it settled on the alluvial fan. In the tail end depression of this tongue a small lake was formed, dammed by the toe of the slide (Fig. 4).

The toe of the slide reached the coast and advanced into the sea, where a steep (37°) escarpment terminates the subaerial part of the slide. This coastal escarpment provides the only exposed section through the slide deposits (Fig. 1); it shows a predominance of matrix-supported conglomerates at the base of the slide and a clast-supported boulder-conglomerate at the top. Locally the slide contains a significant proportion of black shales, probably originating from the mudstone level around 900 m a.s.l.

The coastal escarpment indicates the collapse of a protruding tongue which originally formed the front of the toe. The collapse is believed to have generated a submarine slide and subsequently the tsunami. Volume calculations (see below) suggest that about 30 million m^3 of material slid below sea level.

Effects of the tsunami

The tsunami generated by the landslide affected not only Saqqaq but, as noted above, also the abandoned coal mining village of Qullissat 20 km across the fjord where buildings at altitudes below 30 m a.s.l. were almost completely destroyed. A line of timber debris 100–250 m from the coast marks the upper limit of the tsunami. A hut on the shore at Asuk 20 km from Paatuut (Fig. 2) was completely destroyed.

On the large alluvial fan at the outlet from Ataata Kuua 7 km north-west of Paatuut, several icebergs were stranded 300–700 m from the coast. Wreckage, including fish crates, was scattered across the alluvial fan up to 800 m inland and at altitudes up to 40 m a.s.l., and in the summer of 2001 certain vegetation species in the same area had withered, presumably due to saltwater incursion.

Seismic activity

A seismometer at Qeqertarsuaq registered a distinct seismic signal on 21 November 2000 at 15:05:10 local time (Fig. 6). People in Saqqaq noted that the tsunami arrived at 15:15, and the seismic signal is thus clearly related either to the landslide itself or to an earthquake which triggered the landslide. Seismic stations at Upernavik *c.* 250 km north of Paatuut and at Summit, the drilling camp at the centre of the Inland Ice *c.* 550 km to the east (Fig. 2), also registered a seismic event on 21 November 2000 (Fig. 6). An analysis of the seismic records suggests that a seismic event occurred at 15:04:52 at Paatuut, and that it was probably caused by the release of the basaltic cliff at the head of the slide (Pedersen *et al.* 2001). This event is seen as the arrival of the primary wave (P) and secondary and surface waves (S and Lg) at all stations (Fig. 6). The following stronger signal reflects the surface waves generated by the activity of the avalanche, estimated to have a magnitude of 2.3 on the Richter scale. The constant time difference between the surface waves from the first and the second events at seismic stations at increasing distances from Paatuut indicates that the two seismic signals were generated at Paatuut, separated by approximately one minute. The main slide event was accomplished within approximately 80 seconds. With an average slide distance of 3 km, this implies an average slide velocity of 140 km/h. Maximum velocities would have been close to 200 km/h.

The analysis of the seismic signals does not support the hypothesis that a deep-seated earthquake generated

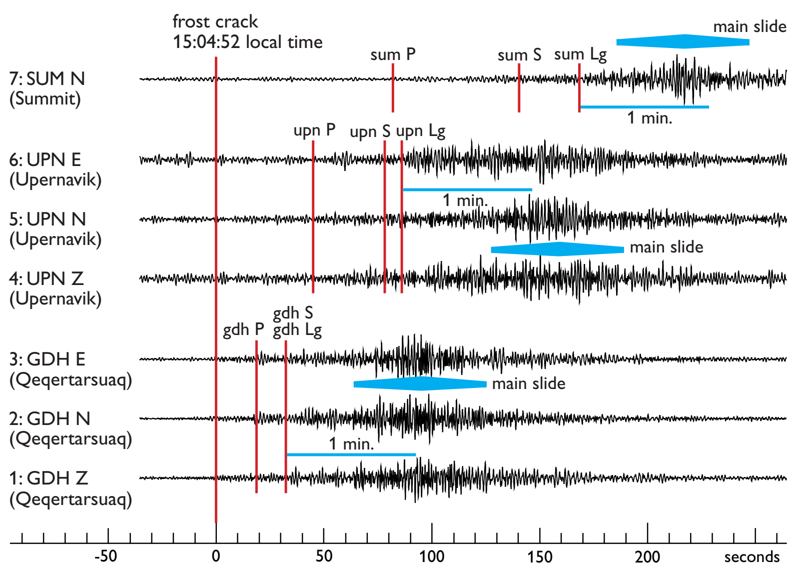


Fig. 6. Seismic events related to the rock fall and landslide at Paatuut 21 November 2000 recorded at Qeqertarsuaq, Upernavik and Summit (Fig. 2). The **red lines** mark the calculated arrival times of **P** (primary), **S** (secondary), and **Lg** (surface) waves from an initial release event at Paatuut. The time is determined by interpreting the P arrival at Qeqertarsuaq. The initial release of the fall occurred at 18:04:52 GMT (15:04:52 local time) and generated P, S and Lg waves. Subsequently, the energy released by the sliding of 90 million m^3 of rocks down onto the coastal slopes is visible as an additional surface wave culminating approximately one minute after the initial event. This second and much larger event – estimated at 2.3 on the Richter scale – is also visible in seismograms from Nuuk, Tasiilaq, Thule and possibly Alert in Canada. **E**, **N** and **Z** are the east–west, north–south and vertical components in the ground movements.

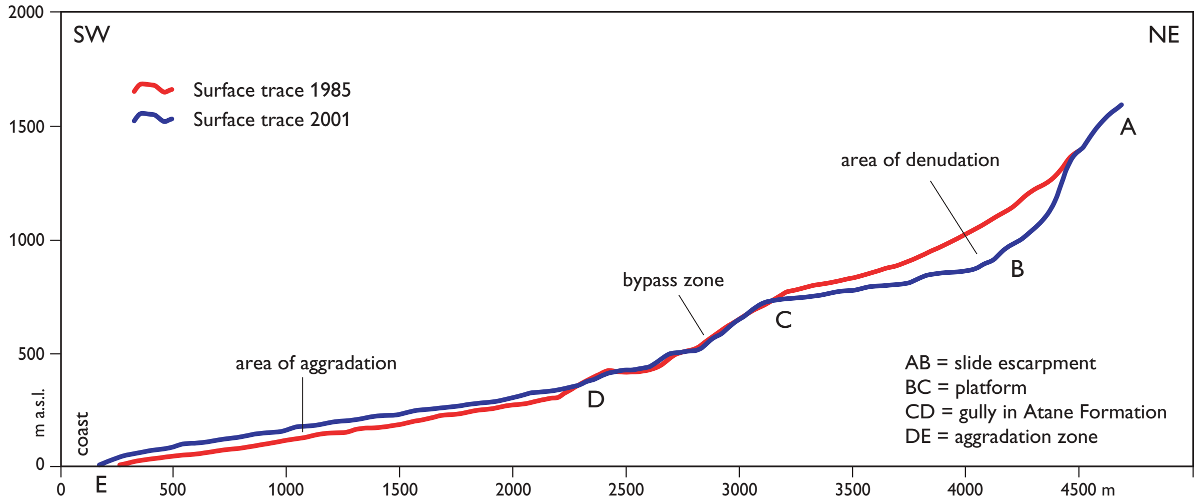


Fig. 7. The relationship between denudation (removal) and aggradation (deposition) regimes in a vertical topographic profile along the landslide area, based on aerial photographs from 1985 and 2001.

the landslide. This is in line with the statistics provided by Keefer (1999), who noted that earthquakes with magnitudes below 4 are unlikely to generate landslides.

Terrain model and volume calculations

Photogrammetrical mapping at the Survey has provided two topographical models of the terrain around Paatuut before and after the landslide. The first model was based on vertical aerial photographs taken in 1985 (scale 1:150 000), and the second model on oblique colour stereo photographs taken with a small-frame camera from a helicopter during the field work in July 2001. From these models (Fig. 7) the volume of displaced material (denudation) has been calculated to *c.* 90 million m^3. The subaerial volume of the toe of the slide (aggradation) amounts to *c.* 60 million m^3, which indicates that *c.* 30 million m^3 of rock material entered the sea giving rise to the tsunami.

Discussion of landslide dynamics

The mechanism that triggered the landslide at Paatuut is open to discussion. The seismic data suggest that the event was initiated by instantaneous fracturing. The appearance of the escarpment at the head of the slide indicates that the escarpment may have formed along a pre-existing fault or fracture zone. The disrupted character of the slide and the number of still ongoing small rock falls accompanied by clouds of dust, as observed in July 2001, support the idea of a fractured cliff. However, the question remains as to what initiated the release of the large volume involved in the slide.

The weather situation in the area prior to the release of the slide may be significant. A week before the event the weather was cold with temperatures below –10°C. Three days before the event a föhn wind blowing from the Inland Ice brought the air temperature up to about +6°C, but on the day before, the weather returned to colder conditions with temperatures down to –6°C. Free water produced during passage of the föhn may have seeped along fractures and fissures, subsequently freezing when it came into contact with the surrounding permafrozen rocks of the cliff and air temperature again dropped below zero. Frost action and resulting increased pore pressure may have triggered the rock fall.

The transformation of the rock fall into an enormous avalanche also raises questions. From the section at the coastal escarpment, black shale can be seen to have been involved in the landslide, and the shale may have acted as a lubricant facilitating the passage of the rock fall. The high velocity of the avalanche during passage through the gullies may have been accentuated by the presence of snow on the slopes. The data available suggest that a combination of grain flow processes and debris flow processes prevailed during transport through the bypass zone.

Grain flow is indicated by the presence of boulders deposited on the shoulders of the gullies at an elevation of 350 m a.s.l. Debris flow is interpreted from the matrix-supported conglomerate at the base of the section at the coastal escarpment, and this is further suggested by the large number of frost-mounds in the flat areas, reflecting the fine-grained character of the subsurface material.

Based on the considerations provided here and on the photogrammetric studies, a four-stage block diagram model of the landslide was constructed and is presented in Fig. 8.

Risk of landslides in the Disko–Nuussuaq–Svartenhuk area

Areas of low risk include most of Svartenhuk Halvø, where the mountains are neither high nor steep, and catastrophic landslides and tsunamis are unlikely to occur. Similarly the south coast of Nuussuaq south-east of Paatuut has a gentle slope, and the basaltic succession is thin and some distance from the coast. Landslides are known to occur in this area (Koch 1959), but mostly as slowly moving coherent slumps or block slides which are unlikely to initiate tsunamis.

Areas of moderate risk are encountered on the north coasts of Disko and Nuussuaq. Around Niaqornat slides form at low altitudes and apparently cause little damage, although houses should not be built closer to the mountain or west of the present village (Pulvertaft

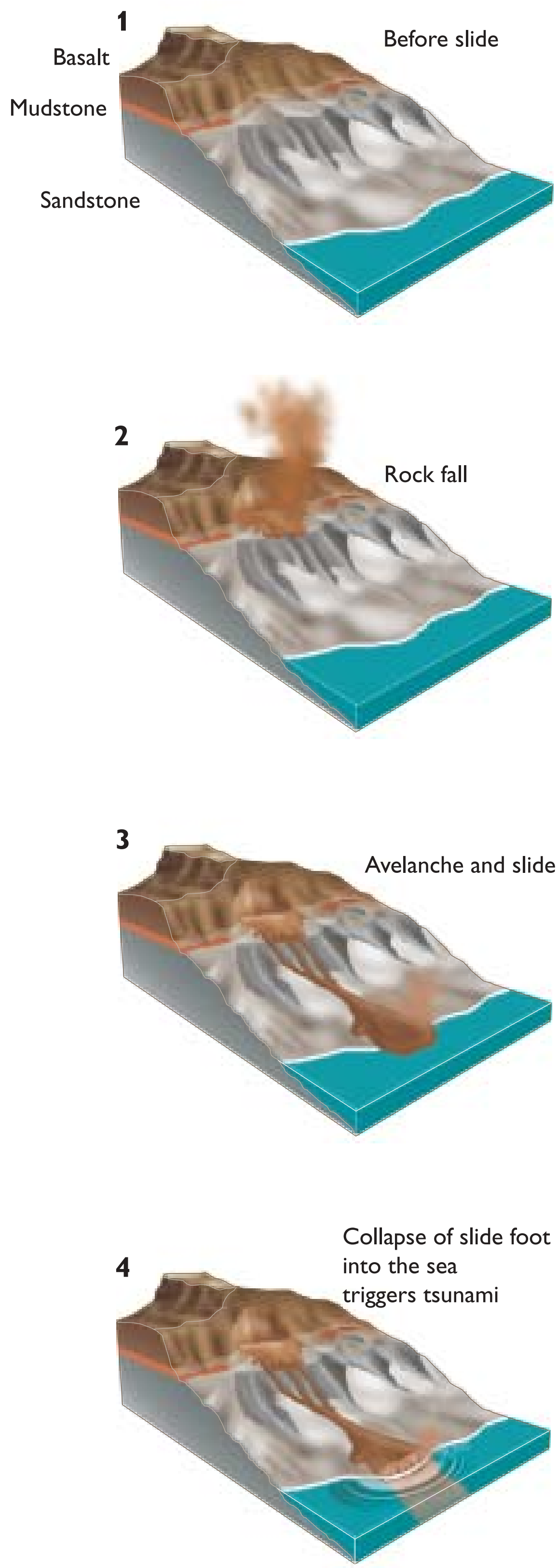


Fig. 8. The development of the landslide event at Paatuut on 21 November 2000, viewed from the west.
1, Cliff and valley slope prior to the landslide event. Note the small crescent-shaped feature in the right side of the diagram which is the head of a slide that was active in the last part of the 1980s.
2, Rock fall is triggered by frost fracturing and cliff cracking at the head of the slide. A large amount of dust is released during the cliff cracking.
3, Rock avalanche, grain flow and debris flow form the deposits at the toe of the landslide, building out into the sea. Note the lobe at the left side of the slide, which is mainly formed by a debris flow squeezed out by gravity spreading from the main landslide aggradation area. In the tailing end depression of this lobe a small lake was later formed, dammed by the toe of the slide.
4, One third of the landslide deposits, forming the tongue built into the sea, subsequently collapses and continues as a submarine slide, generating the tsunami. The steep coastal escarpment constitutes the head of this slide.

1979). Along other sections of the north-facing coasts the slides that occur are slow earth slides or rock glaciers.

Areas with a high risk of landslides accompanied by tsunamis are found on the south coast of Nuussuaq between Paatuut and Nuusap Qaqqarsua (Fig. 2). Here, the very steep slopes and the active erosion of the thick pile of hyaloclastite breccias generate thick, steep, high-lying debris fans, which are unstable and may easily slide.

Studies of aerial photographs show that at least 17 major landslides have occurred in the high-risk section prior to 1985, but only three of these slides are known to have reached the sea. In addition three landslides occurred at Paatuut between 1988 and 2000. Four of the twenty landslides generated within the last 3000 years reached the sea, and the minimum frequency of tsunamis is thus 1–2 per 1000 years. However, two of the four slides occurred within the last 50 years (1952 and 2000), and it may be that some older landslides have not been recognised due to fluvial reworking.

The historical record indicates that catastrophic landslides are not common. The town Qullissat was founded in 1924 and, apart from the slide in 1952 which caused some material damage and the loss of one life, the town has not been damaged by tsunamis in 76 years. In the coastal cliff at Asuk, the tsunami in 2000 disturbed graves several hundred years old. Although the graves were already somewhat damaged by ground creep or perhaps previous tsunamis, it is obvious that a tsunami like the one in 2000 is a rare event.

Prediction of future slides is not possible. However, it is certain that the lithologies and the morphology of the south coast of Nuussuaq from Paatuut and westwards will continue to generate landslides in the future.

Conclusions

The landslide at Paatuut on 21 November 2000 is interpreted as a rock avalanche initiated by a rock fall (Fig. 8). The fall was probably initiated by thawing and freezing in fractures at altitudes of 1000–1400 m a.s.l. The landslide removed 90 million m^3 of scree and volcanic rocks which were transported to the coastal area with an average velocity of about 140 km/h. It built a lobe comprising *c.* 60 million m^3, and *c.* 30 million m^3 continued seawards in a submarine slide which initiated a tsunami and caused heavy damage in the coastal areas of the Vaigat strait. The slide deposited clast-supported conglomerates from modified grain flows, and matrix-supported conglomerates from debris flows. Despite the high risk of landslides on the south coast of Nuussuaq the frequency of catastrophic landslides and tsunamis is not high. The seismic records make the Paatuut 2000 landslide one of the best-documented events of its type.

Acknowledgements

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Authors' addresses

S.A.S.P., L.M.L., T.D.-J., H.F.J., T.N., F.v.P.-H. & W.W., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* E-mail: *sasp@geus.dk*

G.K.P., *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.*

A.K.P., *Geological Museum, University of Copenhagen, Øster Voldgade 5–7, DK-1350 Copenhagen K, Denmark.*

Petroleum geological activities in West Greenland in 2001

Flemming G. Christiansen, Jørgen A. Bojesen-Koefoed, James A. Chalmers, Finn Dalhoff, Christian Marcussen, Tove Nielsen, Henrik Nøhr-Hansen and Martin Sønderholm

Greenland petroleum geological activities at the Geological Survey of Denmark and Greenland (GEUS) during 2001 were focused mainly on the preparation of the 2002 licensing round offshore West Greenland. Promotion of the exploration opportunities in the licensing round area between 63° and 68°N has played an important role together with launching of new seismic and geological projects. Critical evaluation of the results from the Qulleq-1 well drilled in 2000 has continued in this context.

The Statoil group relinquished the eastern subarea of the Fylla licence at the end of April 2000, making all the Qulleq-1 data available for promotion purposes (see Christiansen *et al.* 2001a). The entire remaining area was relinquished by the end of the year. However, as part of outstanding working commitments, the Statoil group acquired approximately 1000 km of new seismic data, mainly from the western part of the licence area. These data have proven to be of great interest for companies evaluating West Greenland (see below). The Phillips group relinquished the entire Sisimiut-West licence area by the end of the year, without entering the next phase of exploration which called for a firm commitment well.

The seismic company TGS-NOPEC extended its activities from 1999 and 2000 with the acquisition of two regional non-exclusive surveys, GreenCan2001 and Green2001. The first is a regional joint-venture programme between TGS-NOPEC and the Bureau of Minerals and Petroleum (BMP), Government of Greenland; the second is a conventional speculative survey, mainly in the northern open-door area (see below).

Several Survey projects relevant to petroleum exploration in West Greenland were finalised in 2001. A study of the Palaeogene succession, combining seismic sequence stratigraphy, sedimentological reinterpretation of petrophysical logs, new biostratigraphy and facies analysis in a sequence stratigraphic framework, is summarised in a paper by Dalhoff *et al.* (2002, this volume). A seismic study of the Palaeogene volcanic rocks from the region west of Disko is also summarised in a separate paper in this volume (Skaarup 2002). Furthermore, a study of potential geohazards in West Greenland, that included a systematic interpretation and mapping of the Neogene succession, was completed (see below).

Two important petroleum geological projects were initiated at GEUS in 2001. One concerns biostratigraphic correlation of the offshore wells from West Greenland and the shelf offshore Labrador, Canada; the other is a regional correlation study of mid-Cretaceous source rocks and oils from West Greenland and North America (see below).

The 2002 licensing round

The 2002 licensing round offshore West Greenland covers the entire area between 63°N and 68°N and thus includes the former Fylla and Sisimiut-West licensing areas. A major effort promoting the petroleum exploration potential has been carried out by BMP in close co-operation with GEUS, the Greenland–Danish national oil company Nunaoil and the owners of major seismic surveys (principally TGS-NOPEC). Numerous presentations on the geology of West Greenland have been given during 2001 at petroleum-related meetings and conferences (Bojesen-Koefoed *et al.* 2001a; Chalmers & Oakey 2001; Chalmers *et al.* 2001a; Christiansen *et al.* 2001b; Dam *et al.* 2001; Middleton *et al.* 2001; Oakey & Chalmers 2001; Rasmussen & Sheldon 2001; Sønderholm *et al.* 2001). Presentations have also been given to a large number of companies both at their own offices in Europe, Canada and the United States and at the Survey's headquarters in Copenhagen.

All relevant information relating to petroleum exploration in West Greenland has been made available on the internet on a newly developed portal: GhexisOnline (www.geus.dk/ghexis). On this site, information on the West Greenland licensing round, geology (including prospectivity, source rocks and maturity, and play types), available data types (well data, seismic data, source rock data, cultural data, etc.), operational conditions, exploration history and relevant literature can be found, together with online versions of the GHEXIS Newsletter.

Geology of Greenland Survey Bulletin 191, 84–89 (2002)

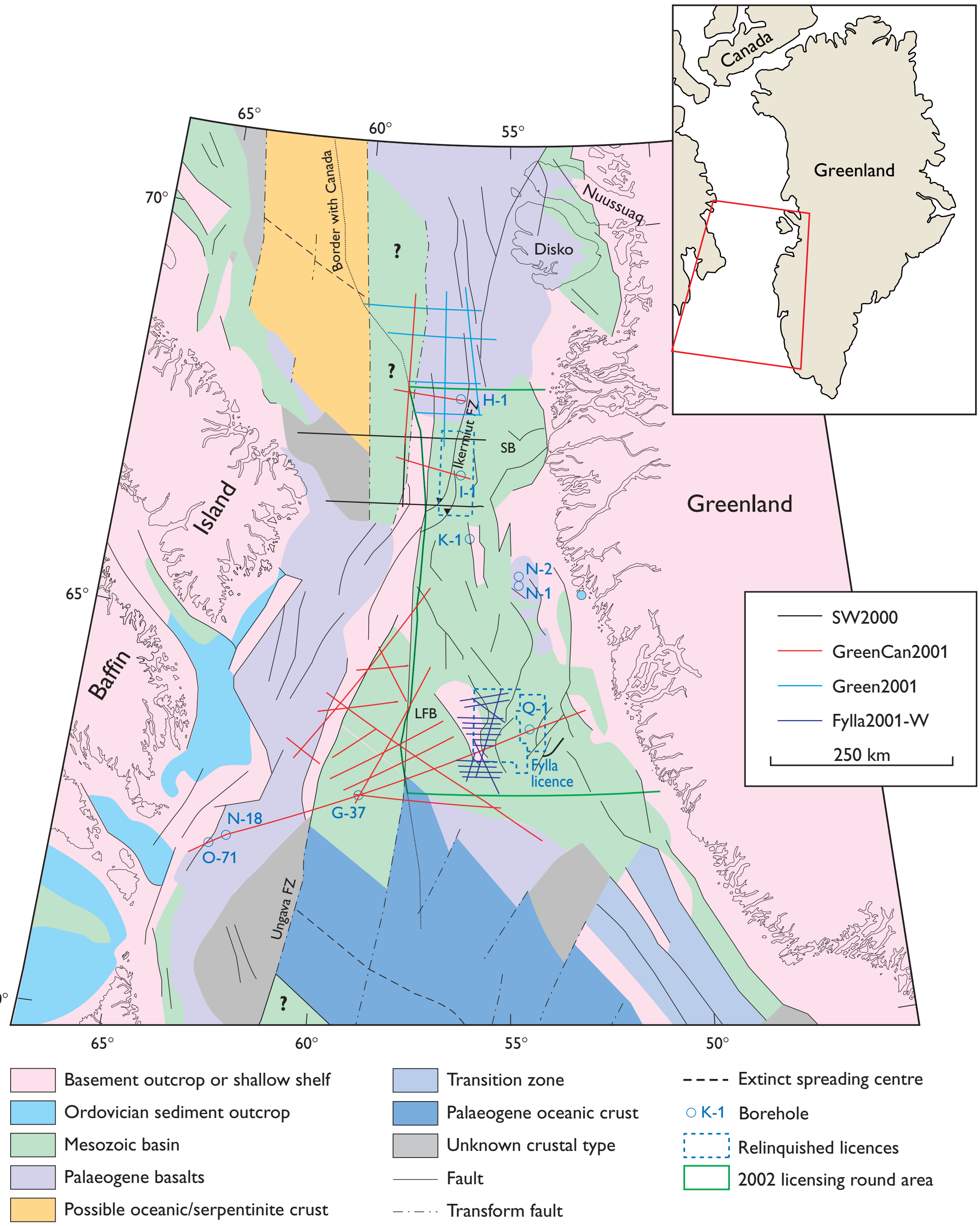

Fig. 1. Map of West Greenland showing main structural elements, sedimentary basins and position of seismic surveys mentioned in text. **SB**: Sisimiut Basin, **LFB**: Lady Franklin Basin, **FZ**: Fault Zone. Two offshore licences were relinquished in 2001: the Fylla licence (Statoil Group) to the south and the Sisimiut-West licence (Phillips Group) to the north.

Seismic acquisition during summer 2001 – the search for the deep basins in the boundary zone between Canada and Greenland

The development of the continental margins of the Labrador Sea is still relatively poorly known due to a limited seismic and geophysical database. The literature and data have recently been reviewed in detail by Chalmers & Pulvertaft (2001). A plate-tectonic reconstruction project has also been initiated in a collaboration between GEUS and the Geological Survey of Canada to increase the geotectonic knowledge of the region (Chalmers & Oakey 2001; Oakey & Chalmers 2001).

In the year 2000, TGS-NOPEC acquired some high-quality seismic lines along the Ungava Fault Zone in the vicinity of the Greenland–Canada border (the SW2000 survey; Fig. 1). These data, in combination with reprocessed satellite gravity data, indicate that deep sedimentary basins that earlier had been recognised in the Sisimiut Basin are more extensive than previously believed (Chalmers *et al.* 2001b; Christiansen *et al.* 2001a). Better mapping of the distribution and internal features of these sedimentary basins may have a significant influence on petroleum exploration concepts in the region. Source rocks older than those already known from the Paleocene, and inferred mid-Cretaceous, may be present in a system of basins along the boundary zone between Greenland and Canada. This is expected to lead to completely new exploration models, both within the deep basins themselves and, due to the possibility of long-distance migration, in the surrounding shallower basin areas.

In order to follow the deeper basins along the Ungava Fault Zone northwards and to outline and study potential kitchens for petroleum generation in the Lady Franklin Basin, the GreenCan2001 survey was acquired during summer 2001 (Fig. 1). A tie-line connecting the Greenland Qulleq-1 well and the Canadian Gjoa G-37, Ralegh N-18 and Hekja O-71 wells was acquired (Fig. 1). This line is important both for tectonic reconstructions and for biostratigraphic/organic geochemical correlations. The survey, which is a regional joint-venture project between TGS-NOPEC and BMP, with GEUS as technical advisor, resulted in a total of 2829 km of seismic data; of these, 1213 km were acquired in Greenland waters and 1616 km in Canadian waters (Fig. 1).

In addition, TGS-NOPEC acquired the Green2001 survey in the northern open-door area (Fig. 1). This survey was designed to follow possible deep basinal trends from the Ungava Fault Zone towards the oil seep region of Disko–Nuussuaq (Christiansen *et al.* 2000). In total, 904 km of seismic data were acquired.

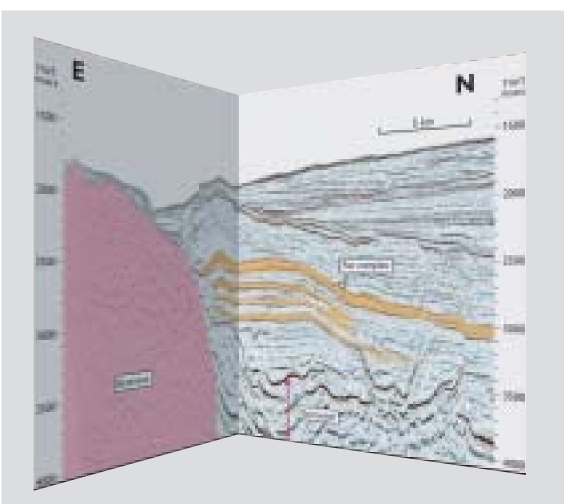

Fig. 2. Seismic lines from the Fylla2001-W survey showing closures at several levels in the Cretaceous succession, primarily as roll-overs formed by later compression along the main Fylla fault.

Seismic acquisition in the western Fylla area

In order to fulfil the remaining work obligations in the Fylla licence, the Statoil group acquired 948 km of seismic data, mainly in the western part of the licence (Fylla2001-W survey; Fig. 1). Although there are some problems in correlating the Cretaceous seismic units across the main Fylla fault, there are good indications from maturity modelling that the inferred Cenomanian–Turonian source rock is thermally mature in this area (Christiansen *et al.* 2001a, fig. 7). The survey was mainly designed to map leads and prospects, either comparable to the Santonian reservoir sandstones known from the Qulleq-1 well, or to contemporaneous or younger hanging-wall and basin floor fans just west of the main Fylla fault. A preliminary inspection of data demonstrates closures at several levels in the Cretaceous succession, primarily as roll-overs formed by later compression along the main Fylla fault (Fig. 2).

With the relinquishment of the Fylla licence, this area is open for licensing in the coming round. A large and modern database is now available which provides opportunities of mapping very large leads and prospects.

The results from the Qulleq-1 well demonstrate the presence of good seals and reservoir rocks and a significant untested up-dip potential (see Christiansen *et al.* 2001a). The main risk, until deeper stratigraphic successions have been penetrated by drilling, is still verification of the presence of good oil-prone source rocks and, in some areas, also thermal maturity.

Geohazard study

During 2001, a study of possible geohazards offshore West Greenland was completed at GEUS in preparation for the 2002 licensing round. Apart from mapping seabed and sub-seabed geohazard features, the post mid-Eocene succession was mapped for the first time using the most important seismic units of regional to semi-regional scale integrated with existing biostratigraphic and well-log data. The mapped seabed geohazard features include bathymetry, gradient, channels, canyons and iceberg ploughmarks, seabed reflector amplitude anomalies, hard bottom and possible 'bottom simulating reflectors' (BSRs), mass flow deposits and current-related features. Sub-seabed features include buried channels and canyons, buried mass flow deposits, diapiric features and dewatering fractures (Fig. 3).

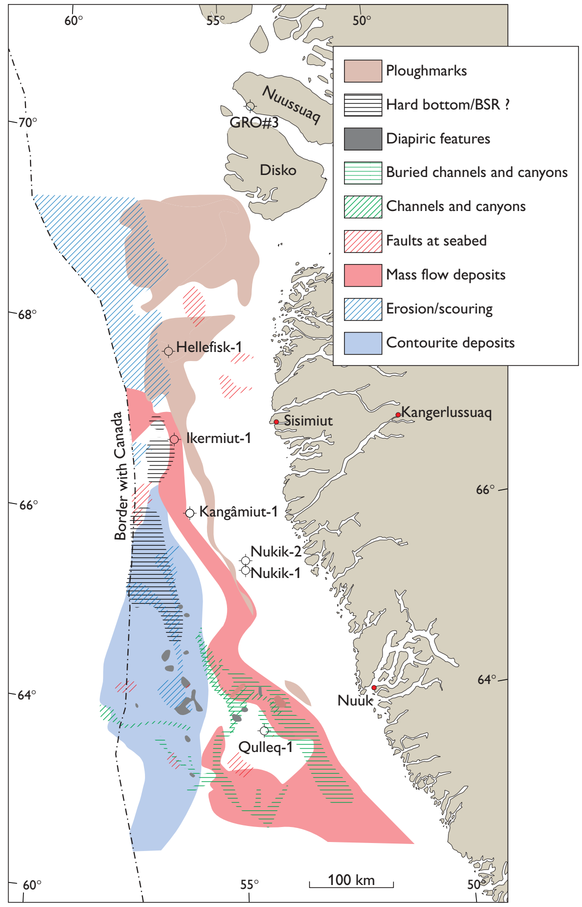

Fig. 3. Map showing compilation of possible geohazard features offshore West Greenland (see text for further details). **BSR**: bottom simulating reflector.

New stratigraphic and source rock studies

Two studies relevant for petroleum exploration were initiated at the Survey in 2001: (1) a biostratigraphic correlation study between West Greenland and Canada, and (2) an organic geochemical project on mid-Cretaceous source rocks and oils throughout the United States and Canada in comparison with West Greenland.

The aim of the first project is to present a biostratigraphic correlation of the West Greenland wells, especially Ikermiut-1 and Qulleq-1 where Cretaceous sediments are present (Nøhr-Hansen 1998; Nøhr-Hansen *et al.* 2000), with selected Canadian wells on the Baffin Island and Labrador shelves (Gjoa G-37, Ralegh N-18, Hekja O-71, Skolp E-07 and Ogmund E-72).

The aim of the second project is to analyse and describe marine oil-prone source rocks deposited during the Cenomanian–Turonian anoxic event (e.g. Schlanger & Jenkyns 1976; Hallam 1987), but also during other periods in the Cretaceous and Palaeogene (especially in the Aptian–Albian and in the Paleocene) in order to erect models for source rock deposition and prediction. The project focuses on a comparison of source rocks and oils in West Greenland with the Arctic basins in Canada and Alaska, the east coast basins of Canada and the United States and basins from the Cretaceous Western Interior Seaway (central Canada and the United States). The provincialism of the fauna and flora of the source rock units will also be addressed in order to test palaeogeographic, palaeo-oceanographic and palaeoclimatic models for the region. In particular, possible seaway connections in Cretaceous time from central West Greenland towards the north (Sverdrup Basin and other Arctic basins), west (Canadian Interior) and south (Atlantic basins) are important for source rock models.

Other petroleum geological work

Although the main focus in 2001 was on the West Greenland 2002 licensing round, field work was also carried out in East Greenland. A project on the post-basaltic, Palaeogene and Neogene sediments in central East Greenland was initiated (Larsen *et al.* 2002, this volume; Nøhr-Hansen & Piasecki 2002, this volume). These sediments have received renewed interest as a result of the recent exploration activities around the Faeroe Islands. Lithostratigraphy, biostratigraphy and sequence stratigraphy studies will provide further insights into basin evolution and uplift history of the northern North Atlantic during Palaeogene time.

After almost 10 years of intensive field work in the Disko–Nuussuaq region in West Greenland, many results important for the evaluation of the exploration potential of the offshore areas are emerging. Although field work was completed in 1999 (Christiansen *et al.* 2000), several studies have been published in 2001, including those on organic geochemistry of coals (Bojesen-Koefoed *et al.* 2001b), sequence stratigraphy (Dam *et al.* 2001), taxonomy (Nøhr-Hansen & Heilmann-Clausen 2001; Nøhr-Hansen *et al.* in press) and discussions of the tectonic history (Chalmers & Pulvertaft 2001). The last of the planned 1:100 000 geological maps of the region was also printed in 2001 (Pedersen *et al.* 2001). Many other studies of basin history, sedimentological and structural models, lithostratigraphy, organic geochemistry of seeps, etc. are in progress.

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *fgc@geus.dk*

A multidisciplinary study of the Palaeogene succession offshore southern West Greenland

Finn Dalhoff, James A. Chalmers, Henrik Nøhr-Hansen, Jan A. Rasmussen, Emma Sheldon and Ulrik Gregersen

A project with the aim of amalgamating an interpretation of reflection seismic data from offshore southern West Greenland with a new interpretation of well data was finalised at the Geological Survey of Denmark and Greenland (GEUS) in 2001 (Chalmers *et al.* 2001b). As part of this study, seismic and depositional sequences between major regional unconformities of Danian and mid-Eocene age were delineated and dated.

New palaeoenvironmental and sedimentological interpretations using dinoflagellate cyst, microfossil and nannoplankton stratigraphies and palaeoenvironmental interpretations from the five exploration wells drilled offshore West Greenland in the 1970s have been combined with a revised interpretation of lithology and correlated with the aid of seismic stratigraphy. The Qulleq-1 well drilled in 2000 was relinquished late in the project period (Christiansen *et al.* 2002, this volume), and it has therefore only been possible to incorporate biostratigraphic information from this well into the project.

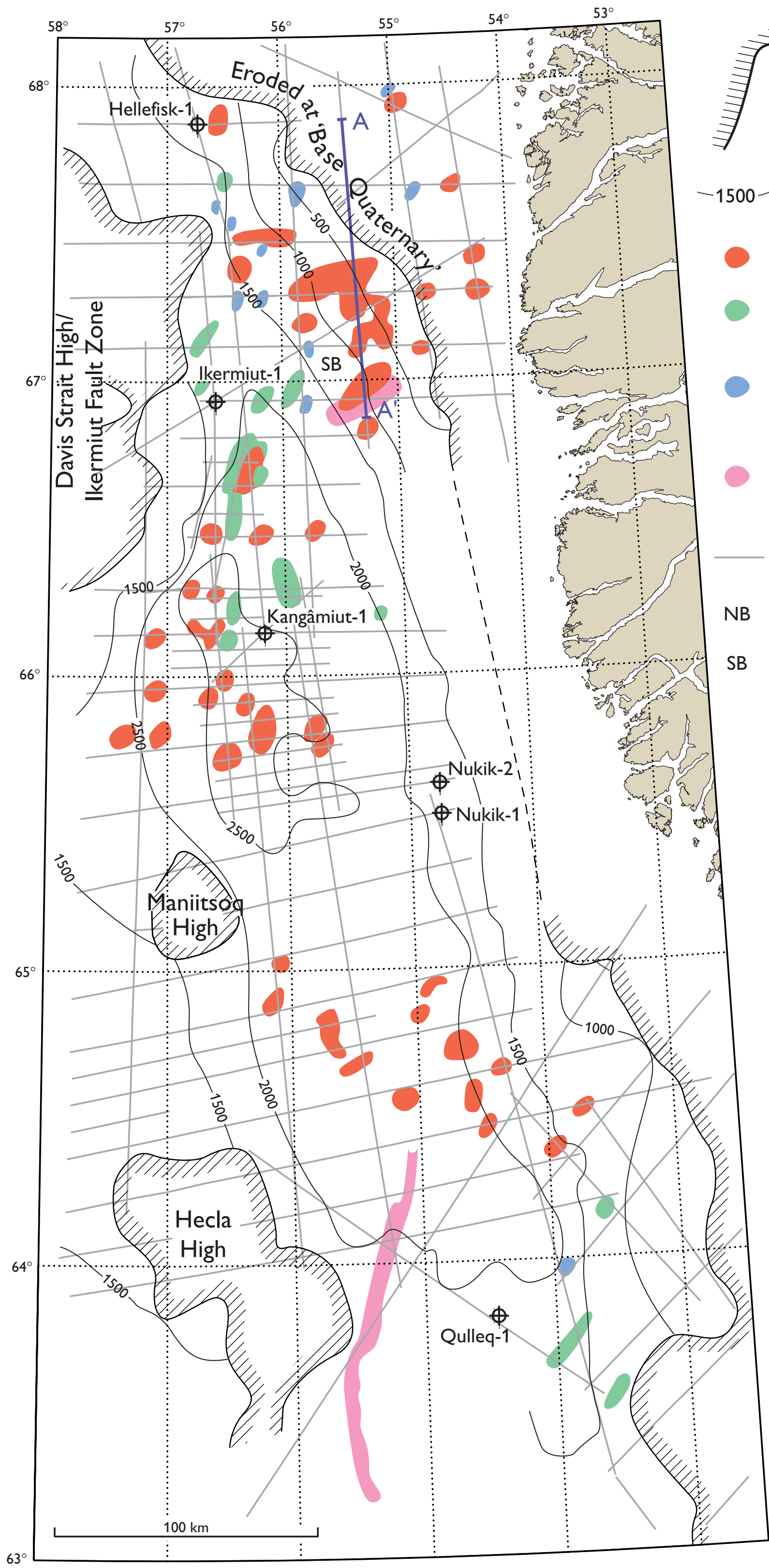
The results show that the region offshore southern West Greenland (Fig. 1) was subject to major uplift and erosion during the Danian, when uppermost Cretaceous sediments were removed. Sedimentation resumed in the late Danian, and was coeval with major volcanism in central West Greenland and the start of sea-floor spreading in the Labrador Sea. Upper Paleocene sediments were deposited in a predominantly extensional tectonic environment. The extensional stresses continued in most areas during the Early Eocene, but in the northern and north-western part of the region, a transtensional system developed along a major strike-slip fault system that transferred sea-floor spreading movements between the Labrador Sea and Baffin Bay.

A stratigraphic framework for the basins offshore southern West Greenland has been erected based on knowledge from the six drilled exploration wells and the onshore exposures of sediments and volcanic rocks in the Nuussuaq Basin and at Cape Dyer, Canada (Rolle 1985; Nøhr-Hansen 1998; Nøhr-Hansen *et al.* 2000; Chalmers *et al.* 2001b; Christiansen *et al.* 2001). Furthermore, seismic sequence studies have been carried out in the southern West Greenland basins (Chalmers *et al.* 1993, 1995, 2001a; Chalmers & Pulvertaft 2001) and these have been compared with the drilled successions offshore Labrador (Balkwill 1987).

Of the five wells drilled in the 1970s, three penetrated only Cenozoic sediments before terminating in Paleocene basalts (Hellefisk-1, Nukik-2) or Precambrian basement (Nukik-1). The Kangâmiut-1 well drilled through an Eocene and younger, sand-dominated succession, then Lower Eocene and Paleocene mudstones, below which the well penetrated a coarse arkosic sand interleaved with mudstone before terminating in Precambrian basement. Only one well from the 1970s (Ikermiut-1) drilled a significant section of pre-Cenozoic sediments, sampling an 850 m mudstone section of Santonian–?Campanian age (unpublished data, H. Nøhr-Hansen 2002) before drilling was stopped. However, the well drilled in 2000 (Qulleq-1), also penetrated thick Campanian mudstones below a Neogene and a thin Palaeogene succession, and terminated in sandstones of Santonian age (Nøhr-Hansen *et al.* 2000; Christiansen *et al.* 2001; Pegrum *et al.* 2001).

The sediments forming the subject of this study lie above a major, regional unconformity of Danian age. The package is bounded above by an unconformity that can be traced over the whole of the southern West Greenland basin (Fig. 1; Chalmers *et al.* 2001a), here referred to as the mid-Eocene unconformity. The sediments immediately above the mid-Eocene unconformity are of middle to late Lutetian age (Nøhr-Hansen 1998, 2001), which coincides with the time at which sea-floor spreading slowed abruptly in the Labrador Sea (magnetochrons 20–21; Roest & Srivastava 1989; Chalmers & Pulvertaft 2001). The package of sediments forming the subject of this report was thus deposited during active sea-floor spreading in the Labrador Sea between magnetochrons 27n and 20r.

Geology of Greenland Survey Bulletin 191, 90–96 (2002)



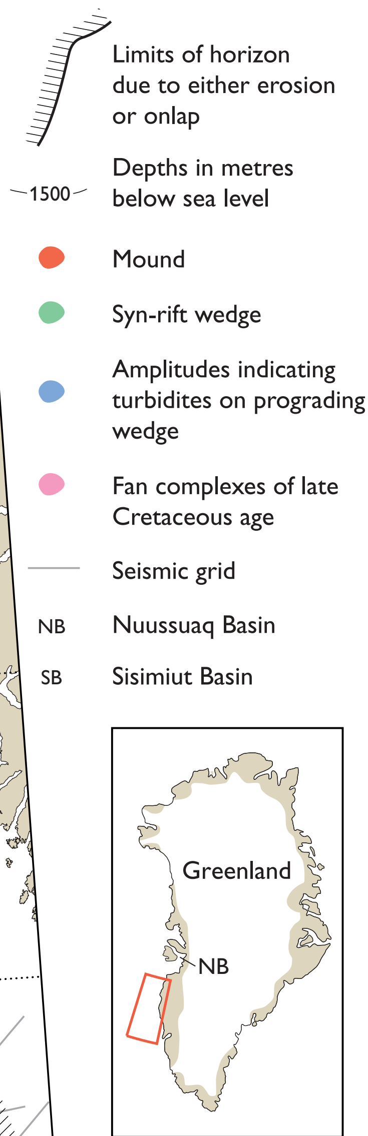


Fig. 1. Locality map showing the extent of the investigated region and the positions of the wells and the seismic lines used to interpret the seismic sequences in this study. The contours show the depths in metres below sea level to the mid-Eocene unconformity. The described Paleocene to mid-Eocene seismic sequences lie under this unconformity, and their distribution shows the maximum extent of the Paleocene to mid-Eocene succession. The map also indicates the distribution of seismic facies representing possible hydrocarbon reservoirs. Seismic line **A–A'** is shown in Fig. 2.

Seismic interpretation

The grid of seismic reflection data used in this interpretation is shown in Fig. 1. The data are all multichannel lines, acquired in 1990, 1991, 1992 and 1995, with the addition of some reprocessed regional lines acquired in 1977. Twenty-nine seismic sequences have been recognised within the studied sediment package, and these seismic sequences have been grouped into 11 third-order depositional sequences (Chalmers *et al.* 2001a). The seismic stratigraphic interpretations have been used to infer two distinct episodes of tectonism. During the Late Paleocene, coinciding with the stage of sea-floor spreading in the Labrador Sea between magnetochrons 27 and 25, tectonism was predominantly extensional. During the Early to Middle Eocene, extension continued in most of the region, but became transpressional along the Ikermiut Fault Zone. Major tectonism ceased during the Middle Eocene at the same time as sea-floor spreading in the Labrador Sea slowed substantially (Chalmers *et al.* 2001a).

A seismic sequence has been identified that is equivalent in age to the sediments that include the Marraat source rock in the Nuussuaq Basin (Bojesen-Koefoed *et al.* 1999). If this seismic sequence also includes a source rock facies, it will be mature for oil generation in the region between the Maniitsoq High and the Kangâmiut-1 well (Chalmers *et al.* 2001a).

In the distal parts of many of the seismic sequences, it is possible to recognise and map discrete seismic facies interpreted as basin-floor fans, syn-tectonic wedges and turbidite channel complexes that could act as hydro-

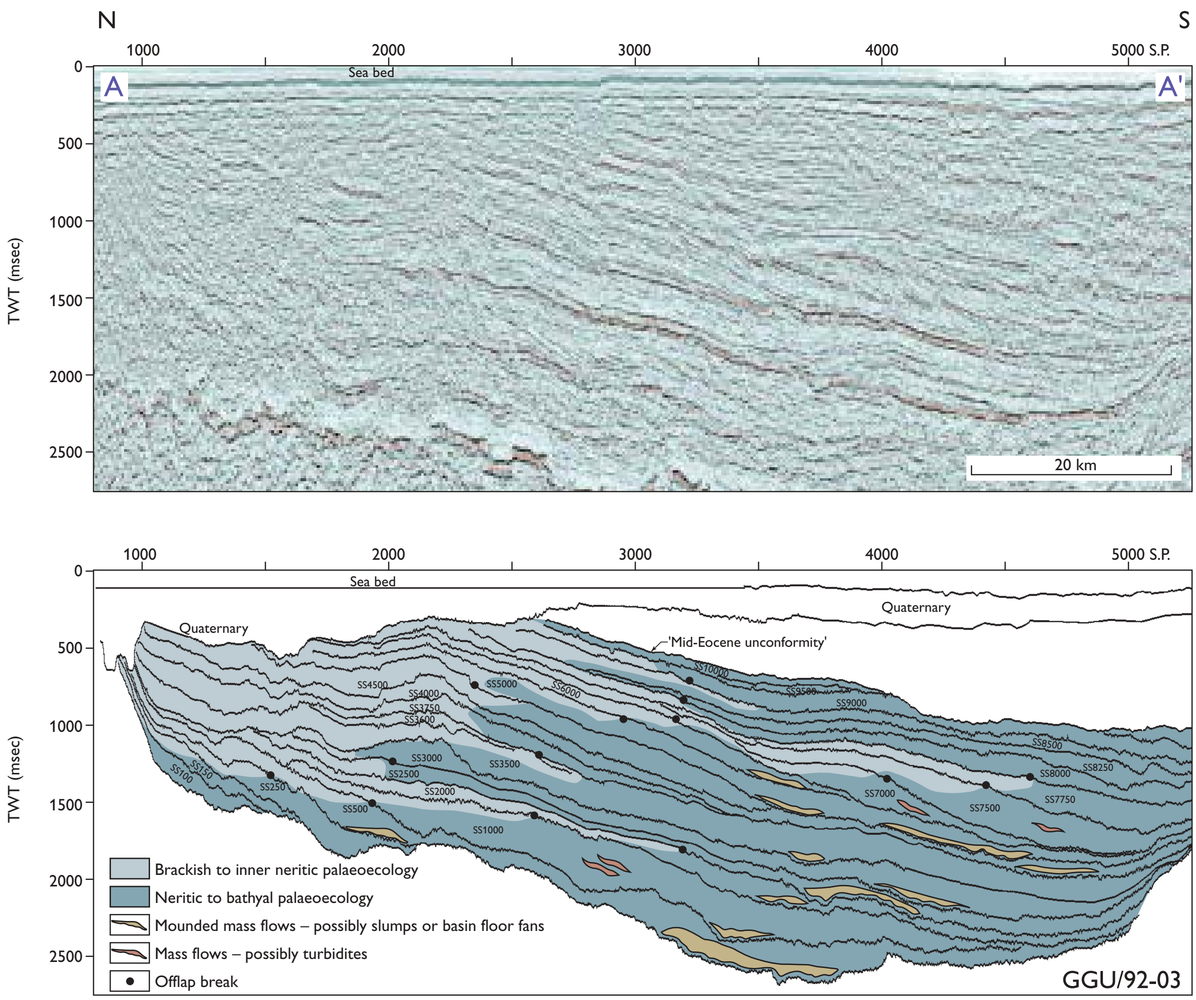


Fig. 2. North–south seismic line GGU/92-03 across the Sisimiut Basin showing the maximum thickness of the seismic sequences. This line illustrates many of the relationships between the seismic sequences, their internal seismic facies and interpretation of palaeoenvironments. For location, see Fig. 1.

carbon reservoirs, sealed by surrounding mudstone (Figs 1, 2). Based on thickness variation throughout the basin it is suggested that sediment input was dominantly from the north, probably representing a continuation of the Cretaceous drainage system from the Nuussuaq Basin, as described by Pedersen & Pulvertaft (1992). Lesser amounts of sediments came from the mainland of Greenland to the east and minor amounts from highs to the west. The sediments were deposited in environments that ranged from freshwater/marginal marine to upper bathyal. Proximal environments are probably generally sand-prone, whereas distal environments probably contain larger amounts of mud, some of which could contain a mature source rock for oil.

Well log interpretation

Sedimentological and palaeoenvironmental interpretations are based on well log interpretation, cuttings and sidewall core descriptions, and palynological and microfossil studies. A lithostratigraphic and biostratigraphic correlation of the five wells from the 1970s offshore West Greenland has been achieved and a log panel displaying correlation of the palyno- and microfossil zonation and seismic sequences is presented here (Fig. 3). Sixteen sequences have been described and dated using log motifs, lithology, microfossils and palynomorphs, and a depositional environment has been suggested for each.

The sediments are predominantly sandstones in the basin-marginal wells (Hellefisk-1, Nukik-1, Nukik-2) and shales in the basin-centre wells (Ikermiut-1, Kangâmiut-1). Based on the re-interpretation of the log data, the sand/shale ratio and facies distributions have been modified from that presented by Rolle (1985). Most of the Palaeogene sediments in Hellefisk-1, Nukik-1, and to a certain degree Nukik-2, were deposited in a littoral to inner neritic environment, whereas most Palaeogene sediments in Kangâmiut-1 and Ikermiut-1 were deposited in an outer neritic to bathyal turbiditic environment (Dalhoff *et al.* 2001).

Biostratigraphy

A new Palaeogene dinoflagellate cyst stratigraphy from offshore West Greenland has been described based on data from the Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2 and Qulleq-1 wells (Nøhr-Hansen 2001). The dinoflagellate cyst stratigraphy has been correlated with the microfossil zonation and previously established zonations in the North Sea. Twenty-one stratigraphic intervals are defined from the upper Lower Paleocene to the Upper Eocene. The stratigraphy and well correlation are based on last appearance datum events and abundances of stratigraphically important species from 355 samples, 148 of which are sidewall core samples.

A nannofossil study has been carried out in the Kangâmiut-1 and Nukik-2 wells (Sheldon 2001). The stratigraphy has been correlated with previously established nannofossil zonation schemes and, where possible, used to indicate palaeoenvironmental changes during the Early and Middle Eocene. The stratigraphy and dating are based on stratigraphically important species, and palaeoenvironmental signals are based on species influxes. A total of 69 samples (26 sidewall cores and 43 ditch cuttings samples) were examined and compared with findings from nearby DSDP and ODP sites.

A microfossil-based biostratigraphy of the Paleocene and Lower Eocene sediments of the Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1 and Nukik-2 wells has been established (Rasmussen & Sheldon 2001). In general, the five wells contain fairly well-preserved, diverse microfossil faunas and floras consisting mainly of foraminifera, radiolaria, ostracods, bivalves and fish remains, together with diatom and palynomorph floras. Nannofloras (mainly coccoliths) occur in relatively low numbers (Sheldon 2001). The biozones are more easily recognised in the two basinal wells (Ikermiut-1 and Kangâmiut-1) than in the three more nearshore wells (Nukik-1, Nukik-2 and Hellefisk-1) due to a higher microfossil diversity and abundance.

The Middle Eocene and upper Lower Eocene intervals of the Hellefisk-1 well in particular are poorly represented by microfauna, with samples often being barren or only containing coal fragments.

Concluding remarks

The new interpretation of seismic and well data suggests that an equivalent to the Marraat oil source rock may be present – and mature – in large parts of the Sisimiut Basin. The Marraat oil, one of the oils that have been discovered seeping to the surface in the Nuussuaq Basin, has been attributed to a source rock not older than the latest Cretaceous (Bojesen-Koefoed *et al.* 1999). The source rock appears to have been encountered in the GRO#3 well (Christiansen *et al.* 1999), and this interval is dated as belonging to the Early Paleocene (Nøhr-Hansen *et al.* in press). Only the lower part of sequence

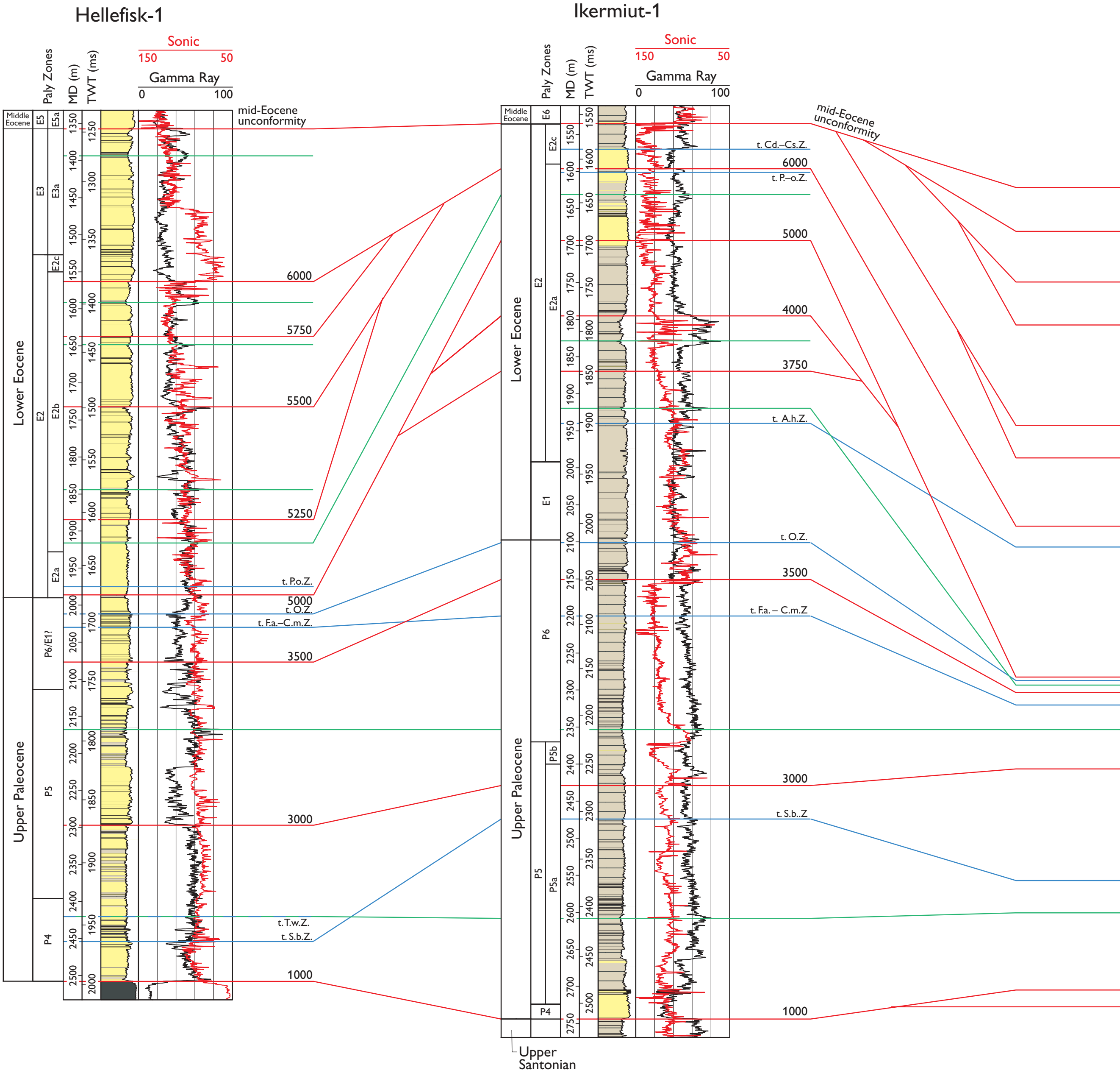


Fig. 3. Log panel showing the correlation of the Palaeogene succession in the five wells from offshore West Greenland drilled in the 1970s. The seismic sequences are numbered sequentially (500–10 000); the marine flooding surface within sequence 3000 is used as the datum. It should be noticed that some sequences are very local, especially above Sequence 6000 in the Kangâmiut-1 well. The crossing between the *A. hirtus* Zone correlation line and the seismic sequence boundaries between Ikermiut-1 and Kangâmiut-1 may be explained by a lower resolution of the former. The palynological zonation adopted here is based on that of Bujak & Mudge (1994) and Mudge & Bujak (1996a, b). Modified from Dalhoff *et al.* (2001).

SS500 and older seismic sequences are as old as this, and the extent of an equivalent to the Marraat oil source rock is restricted to the extent of SS500 (Chalmers *et al.* 2001a, figs 8, 31).

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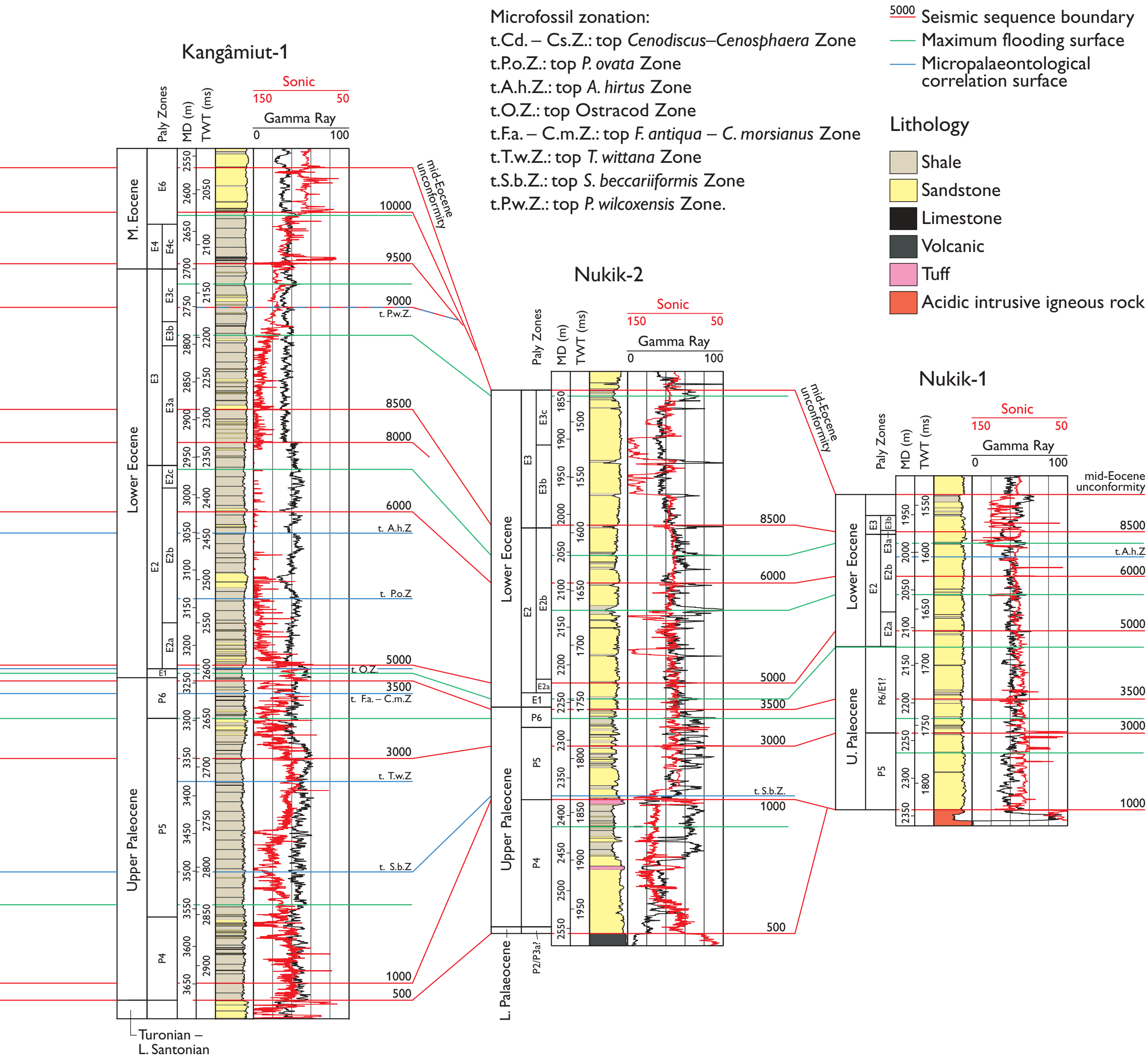

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Authors' addresses

F.D., J.A.C., H.N.-H., J.A.R. & E.S., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.*
E-mail: *fd@geus.dk*

U.G., *Bureau of Minerals and Petroleum, Government of Greenland, P.O. Box 930, DK-3900 Nuuk, Greenland.*

Evidence for continental crust in the offshore Palaeogene volcanic province, central West Greenland

Nina Skaarup

The Palaeogene volcanic province of central West Greenland extends for 550 km from north to south and 200 km from east to west (Henderson 1973; Henderson *et al.* 1981; Whittaker 1996). In a preliminary interpretation of the area offshore Disko and Nuussuaq, based on older seismic data, Whittaker (1996) described a number of large rotated fault blocks containing structural closures at top volcanic level that could indicate leads capable of trapping hydrocarbons. This work, combined with the discovery of oil in the basalts onshore, led the Geological Survey of Denmark and Greenland (GEUS) to acquire 1960 km of multi-channel 2D seismic data in the area between 68°N and 71°N in 1995 (Fig. 1). These seismic data are the primary data source for the interpretation presented in this paper.

By combining the interpretation of the seismic data with modelling of gravity data, the possibility of oceanic crust being present in the volcanic offshore area has been tested. It has been found that the observed gravity field is inconsistent with the presence of oceanic crust, whereas continental crust with sediments below the volcanic section fits the modelling. In the uppermost part of the offshore volcanic rocks, divergent flow directions indicate the presence of an eruption zone (Skaarup 2001). Dating of onshore volcanic rocks, a new date from an offshore well, and the interpretation of seismic units suggest that the volcanic rocks in the offshore area were erupted at the earliest during magnetic chron C26r (60.9–58.4 Ma), and not much later than C24n (53.6–52.4 Ma).

Structures, stratigraphy and thickness of the offshore volcanic rocks

Volcanic rocks have been mapped in the offshore area between 68°N and 71°N (Fig. 1). The top volcanic surface crops out close to the western coast of Nuussuaq and Disko, and dips westwards below sediments of Eocene age and younger. The volcanic rocks are not limited to this area, but continue west of longitude 58°30´W, which is the western limit of the data.

Structures at top volcanic level have been interpreted and mapped. The fault pattern is dominated by steep, normal faults with N–S trends curving towards the northwest north of latitude 70°30´N (Fig. 1). The major faults outline horst and graben structures and complex minor faulting is commonly found within the grabens (Skaarup *et al.* 2000). This structural system is probably associated with transform strike-slip faults arising from sea-floor spreading in Labrador Sea and Baffin Bay (Chalmers *et al.* 1993).

The volcanic section can be divided into five mappable seismic units (Figs 1A, 2). The predominant seismic facies in the volcanic rocks is parallel to subparallel, with various degrees of downlap. These parallel-bedded units pass into downlapping units of both oblique and sigmoidal to almost chaotic hummocky clinoforms (Fig. 2). They form a direct equivalent to the onshore exposures where horizontal subaerial volcanic rocks pass into downlapping subaqueous hyaloclastites (Pedersen *et al.* 1993).

On several seismic lines, foresets in the uppermost volcanic unit show divergence eastwards and westwards (Fig. 1B). This indicates the presence of an eruption zone, and the pattern of distribution suggests that it is dissected into several en échelon segments as seen on Iceland at the mid-Atlantic Ridge.

Gravity modelling

It has not been possible to interpret the base of the volcanic rocks from the seismic data alone, mainly because of the transmission loss of the seismic signal within the volcanic rocks. Modelling of the thickness of the volcanic rocks can, however, be carried out by combining gravity data and seismic interpretation.

Onshore western Disko, a monoclinal flexuring of the basaltic succession has been interpreted to represent a seaward-dipping reflector sequence derived from a plume-related plate break-up (Geoffroy *et al.* 1998, 2001). According to this interpretation the ocean–con-

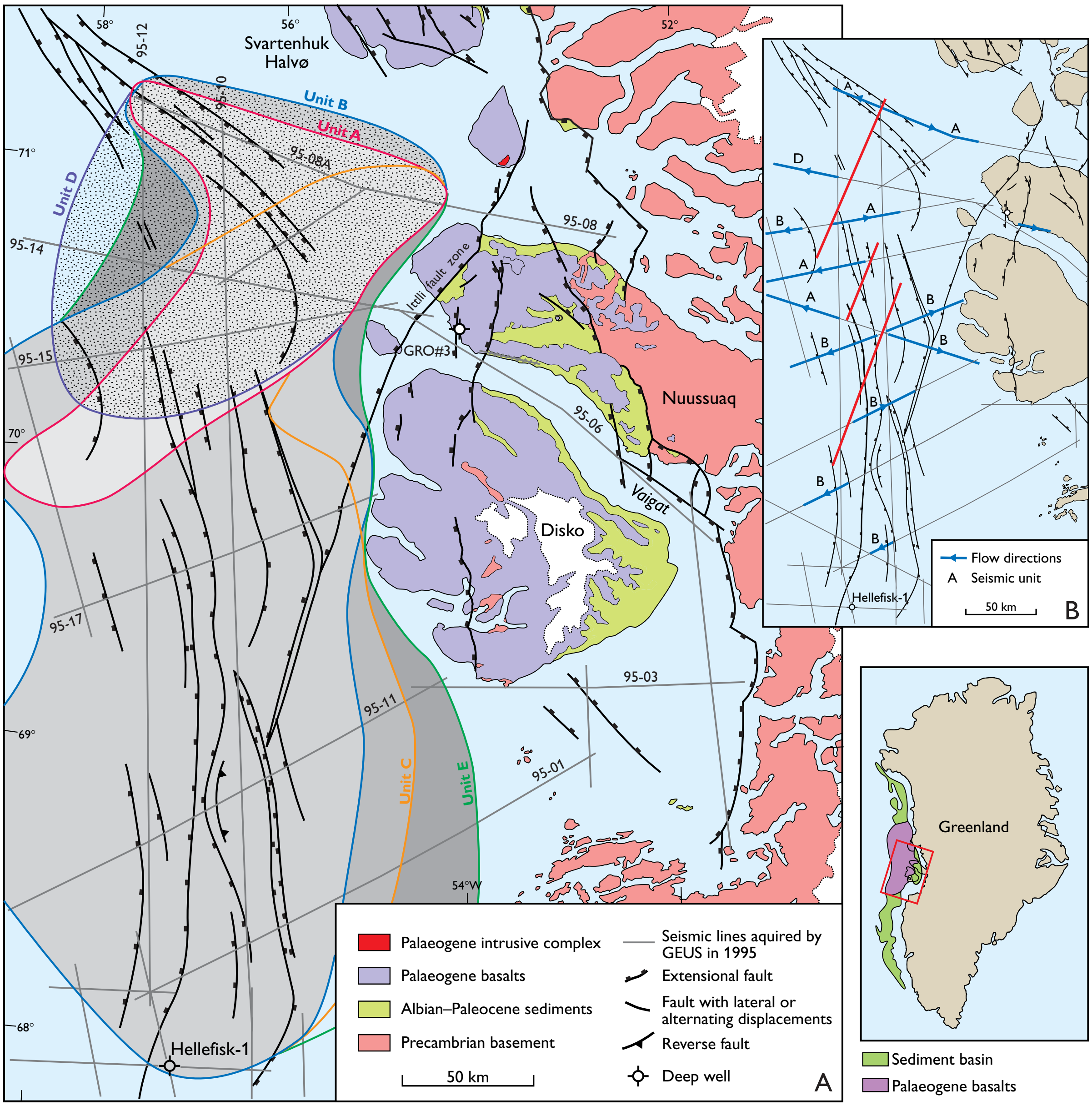
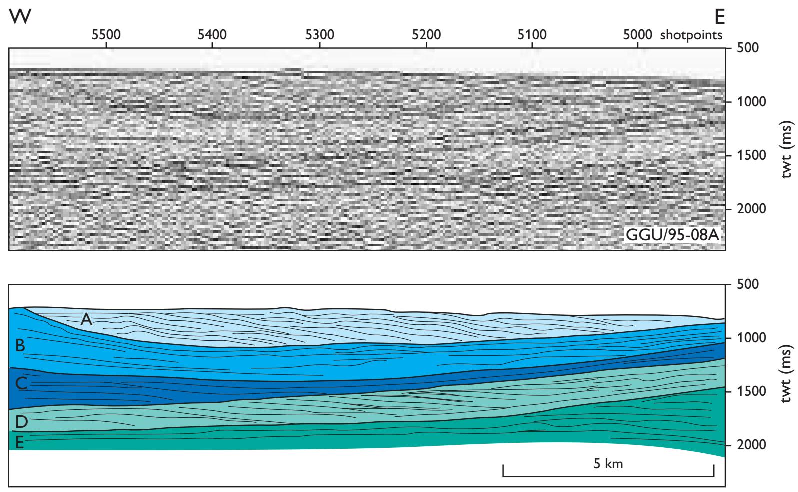


Fig. 1. **A**: Map of the study area showing structures at top volcanic level and the distribution of seismic units A–E. Onshore geology slightly modified from Chalmers *et al.* (1999). White areas are ice. **B**: The eruption zone in the offshore area marked by the en échelon segments interpreted from divergence of the volcanic foreset directions observed in seismic units **A**, **B** and **D** (indicated).

tinent boundary lies close to the west coast of Disko. This hypothesis may be tested by modelling two scenarios of ocean crust offshore Disko: a warm, Icelandic plume type and a cool, normal type. In the 'warm' model, Moho is assumed to lie at a depth of 25 km, and the continental crust has been terminated a short distance offshore. This model results in a difference between the calculated and measured gravity data of 120–160 mGal in the area of assumed oceanic crust. In the 'cool' model, the Moho is assumed to lie at a depth of 12–13 km. This model shows an even greater difference between calculated and measured gravity data amounting to 250–300 mGal. The most likely solution to reducing the excess mass in these models is by incorporating a layer of sediment. Further modelling was carried out assuming continental crust in the offshore

Fig. 2. Part of seismic line GGU/95-08A, just north-west of Nuussuaq. Several basin fill structures can be seen as seismic units **A–E**. In this area seismic unit A has a strongly downlapping appearance where the top reflection passes into eastward prograding facies. The vertical height of the downlapping units is 700–800 m, which is directly equivalent to the 700 m high foresets observed in the Vaigat Formation on the south coast of Nuussuaq (Pedersen *et al.* 1993).



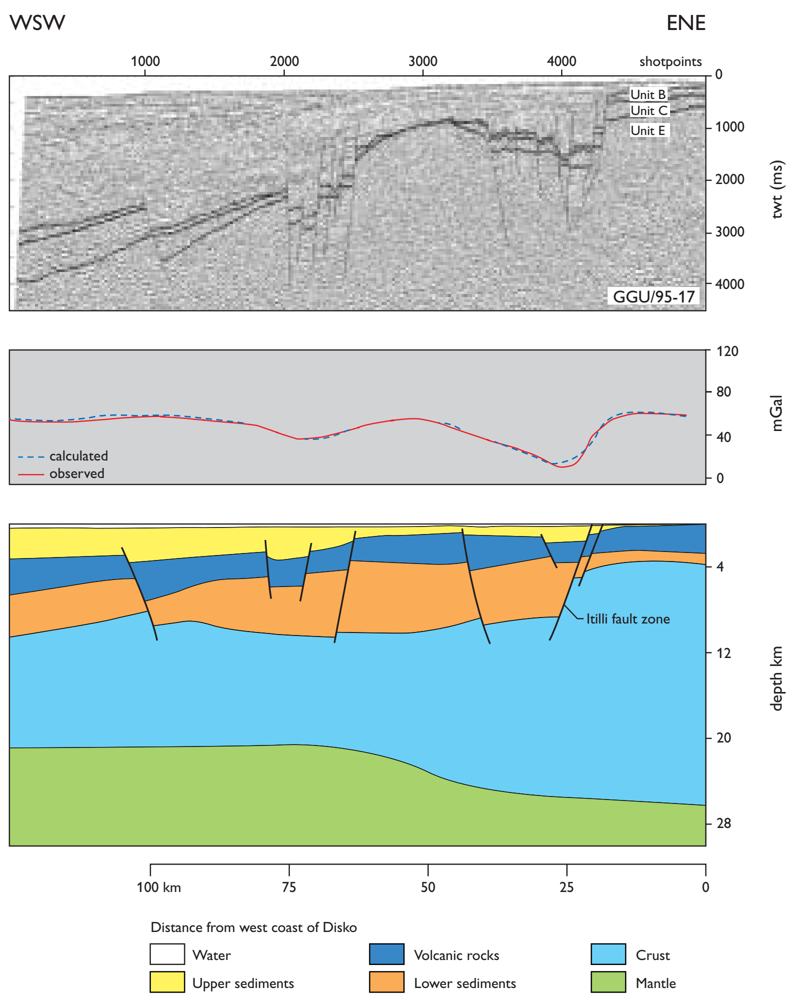


Fig. 3. Geological model of the region west of Disko based on gravity modelling assuming continental crust in the offshore area. Based on onshore geological data, a rather uniform thickness of 2.5–3.5 km has been assigned to the volcanic section. The depression in the gravity signal west of the Itilli fault zone is partly compensated by a postulated abrupt increase in thickness of the pre-volcanic sediments and by a change in the topography of the volcanic surface.

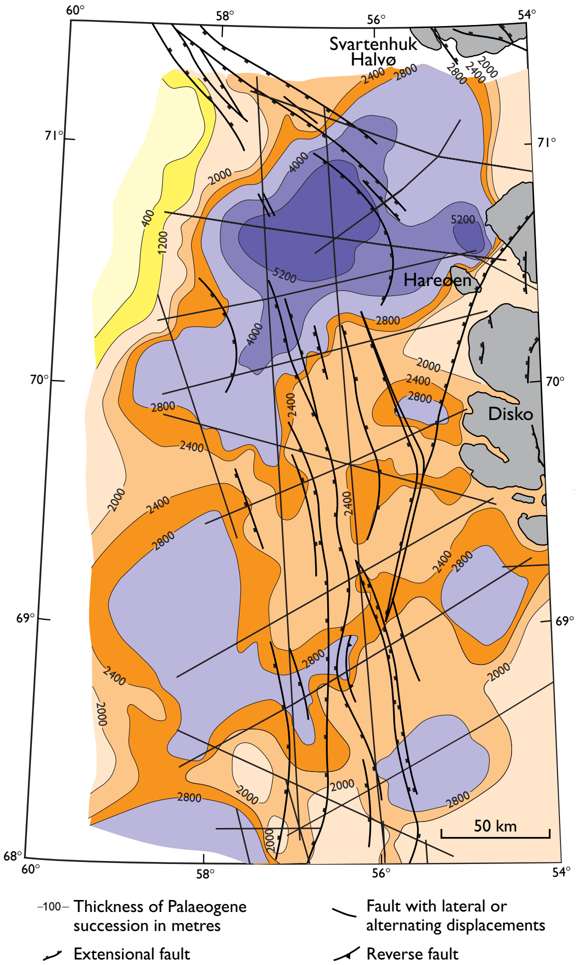


Fig. 4. Isopach map of the Palaeogene volcanic succession, based on the results of the gravity modelling. The isolines showing the thickness of the volcanic section curve around Disko and display thicknesses of 2.5–3.5 km, with a local maximum just west of Hareøen with more than 5 km. The determination of the base of the volcanic section is based only on gravity modelling, since it cannot be seen on the seismic data.

area and sediments between the volcanic rocks and the continental basement.

In order to further constrain the modelling, geological data from onshore Disko and Nuussuaq have been incorporated into the model shown in Fig. 3. The Palaeogene volcanic rocks on western Nuussuaq comprise the Maligât Formation (estimated thickness *c.* 3 km) and the 1–2 km thick Paleocene–Eocene Vaigat Formation (Chalmers *et al.* 1999). On the south coast of Nuussuaq, the GRO#3 well recorded at least 2700 m of Upper Cretaceous sediments below the volcanic rocks (Christiansen *et al.* 1999). Fifteen kilometres to the east of the GRO#3 well (Fig. 1A) a short seismic line shows at least 4.5–6 km, and possibly as much as 7–8 km of sediments below the volcanic section (Christiansen *et al.* 1995; Chalmers *et al.* 1999). Furthermore, the occurrence of sedimentary xenoliths and metallic iron in many volcanic rocks on western Disko, is strongly indicative of the presence of pre-volcanic sediments there (Pedersen 1981).

The resulting model (Fig. 3) shows a good correlation between the observed and calculated gravity data supporting the contention that the region offshore Disko and Nuussuaq is underlain by continental and not oceanic crust.

There is, of course, no unique solution to the gravity modelling. It must, however, be based on all available geological data and in the end show a good fit between the observed and calculated gravity data. The offshore volcanic succession thickens towards the west (Fig. 4). The sedimentary section below the volcanic rocks displays more or less the same outline as the volcanic rocks, where the sedimentary basin deepens very rapidly off the coast to attain a maximum thickness of 7–9 km (Fig. 3; Skaarup *et al.* 2000).

Dating of the offshore volcanic rocks

An estimate of the age of the offshore volcanic rocks can be given by comparing the seismic interpretation of the volcanic units in the offshore area with an Ar/Ar age determination from the offshore Hellefisk-1 well and with Ar/Ar and K/Ar age determinations and geomagnetic polarity determinations from onshore exposures.

Onshore, most of the exposed volcanic rocks were erupted in two phases (Storey *et al.* 1998; Riisager & Abrahamsen 1999). The first phase (represented by the Vaigat and Maligât Formations) between 60.7 Ma and 59.4 Ma and the second, mainly represented by dykes, between 54.8 Ma and 53.6 Ma (Fig. 5). Offshore, the uppermost seismic unit (unit A) is normally magnetised (Rasmussen 2002, this volume) and probably overlies the offshore equivalent to the youngest volcanic rocks on western Nuussuaq. The onshore volcanic rocks are reversely magnetised (Riisager *et al.* 1999) and were possibly erupted during magnetic chron C24r. Therefore, seismic unit A could have been erupted during chron C24n. Seismic unit B is interpreted to reach the Hellefisk-1 well, where an Ar/Ar date shows an age of 57.7 ± 1.2 Ma (Williamson *et al.* 2001), and seismic unit B could have been erupted during C25 at the latest, and more probably during C26.

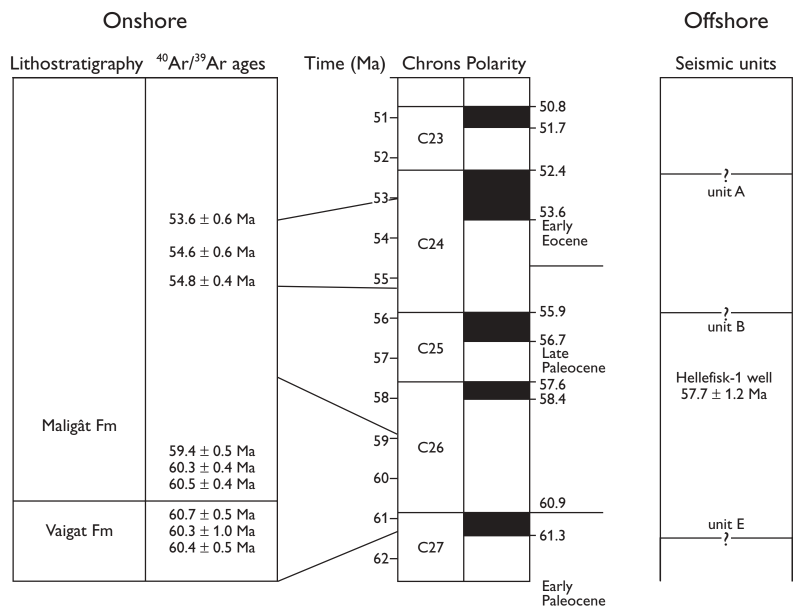


Fig. 5. Overview of the onshore volcanic succession compared to the seismic units in the offshore area. The lithostratigraphy and $^{40}Ar/^{39}Ar$ ages are from Storey *et al.* (1998), the $^{40}K/^{40}Ar$ date for the Svartenhuk dykes from Geoffroy *et al.* (2001), the geomagnetic time scale from Cande & Kent (1995), the measurements of the magnetic chrons and reversals in the Vaigat and Maligât Formations from Riisager & Abrahamsen (1999) and Riisager *et al.* (1999) and the $^{40}Ar/^{39}Ar$ measurement from the Hellefisk-1 well from Williamson *et al.* (2001).

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Author's address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *nsk@geus.dk*

The post-basaltic Palaeogene and Neogene sediments at Kap Dalton and Savoia Halvø, East Greenland

Michael Larsen, Stefan Piasecki and Lars Stemmerik

The Palaeogene flood basalts in East Greenland are part of the North Atlantic Igneous Province (NAIP) formed during continental rifting and opening of the northern North Atlantic (Saunders *et al.* 1997). Along the Blosseville Kyst in southern and central East Greenland the basalts are exposed onshore from Kangerlussuaq in the south to Scoresby Sund in the north (Larsen *et al.* 1989). The base of the volcanic succession is exposed at Kangerlussuaq and at Savoia Halvø whereas post-basaltic sediments are found at two isolated localities, Kap Dalton and Savoia Halvø (Fig. 2). These three outcrop areas are thus key sources for biostratigraphic data to constrain the onset and duration of the Palaeogene volcanism in East Greenland, and are widely used in reconstructions of the North Atlantic region during continental break-up (e.g. Clift *et al.* 1998; Dam *et al.* 1999). In August 2001 the Geological Survey of Denmark and Greenland (GEUS) carried out field work in the sedimentary successions at Kap Dalton and Savoia Halvø. This was the first visit by geologists to Kap Dalton since 1975, and it is expected that the new data will provide important new biostratigraphic information and help to refine models for the Palaeogene of the North Atlantic. This report, and the palynological study of the sediments immediately below the basalts at Savoia Halvø presented by Nøhr-Hansen & Piasecki (2002, this volume), present the preliminary results of the field work.

Previous work

The presence of sediments at Kap Dalton was first recognised by O. Nordenskjöld and N.E.K. Hartz in 1900 during the Amdrup–Hartz Expedition to East Greenland (Fig. 1; Hartz 1902). A collection of sedimentary rocks and fossils brought back by the expedition was examined by Ravn (1904) and formed the basis for dividing the succession into the sandy '*Cyrena* Beds' and the shaly '*Coeloma* Beds'. Both units were interpreted to be of Eocene age by comparison with West European marine faunas, although the close resemblance between the Greenlandic crustacean *Coeloma bicarinatum* in the '*Coeloma* Beds' and European Middle Oligocene species was noted (Ravn 1904).

New studies of the sedimentary succession at Kap Dalton were undertaken by L.R. Wager during the Scoresby Sound Committee's 2nd East Greenland Expedition in 1932 (Wager 1935). Wager recognised a

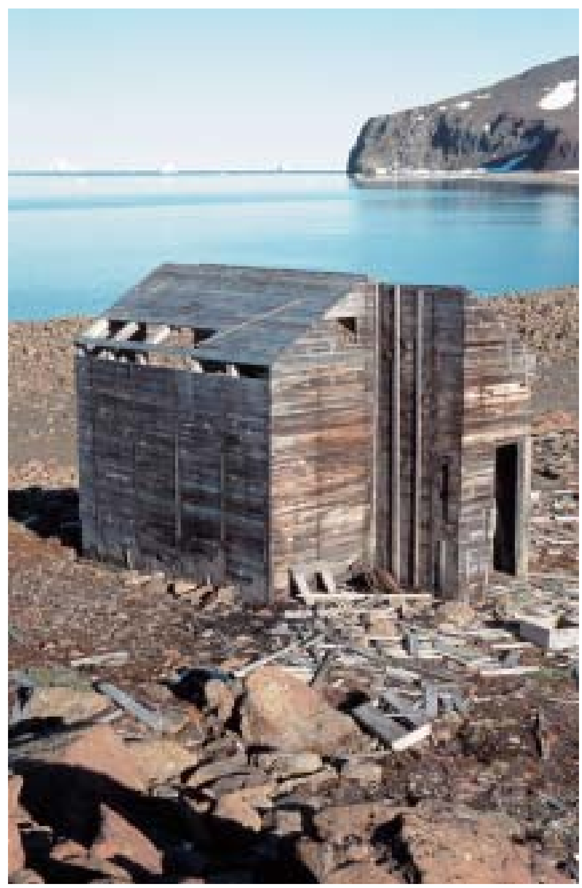

Fig. 1. The Amdrup–Hartz depot hut in the bay north-west of the basaltic headland Kap Dalton.

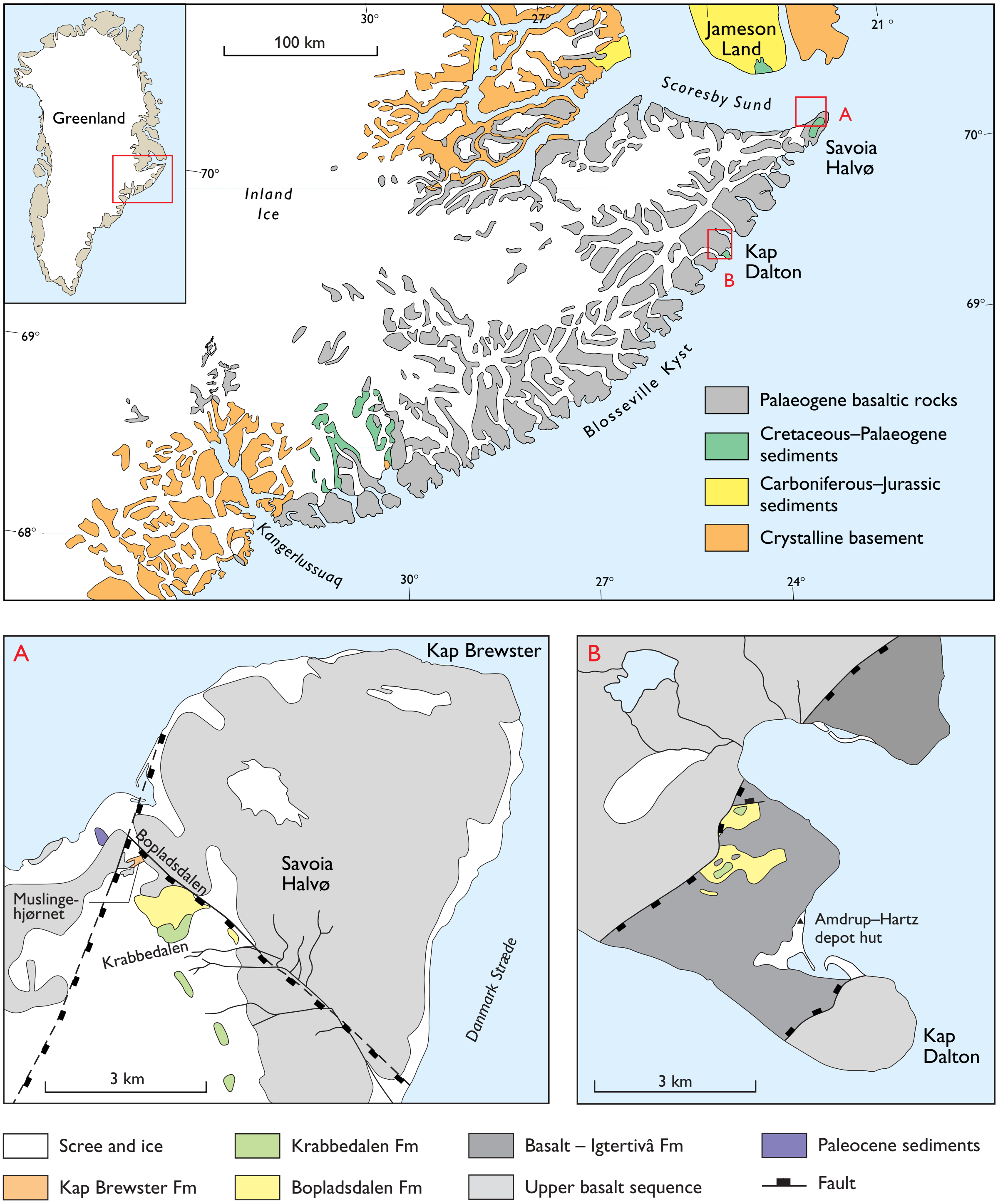

Fig. 2. Map of central and southern East Greenland showing distribution of the Carboniferous–Palaeogene sediments and Palaeogene flood basalts. **A**: Savoia Halvø; **B**: Kap Dalton (modified from, respectively, Nøhr-Hansen & Piasecki 2002, this volume and Birkenmajer 1972).

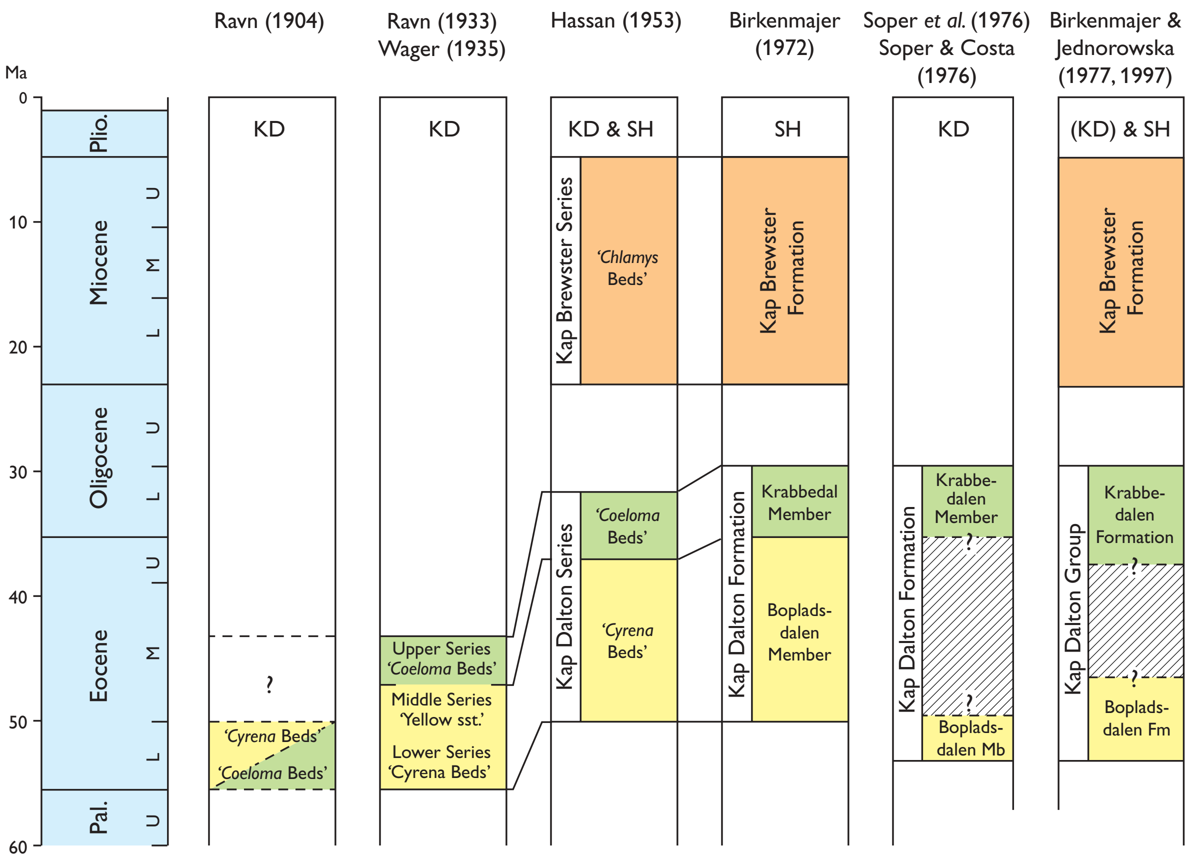

Fig. 3. Stratigraphic scheme showing different interpretations of the Palaeogene sediments at Kap Dalton (**KD**) and Savoia Halvø (**SH**).

small graben structure in which the top of the basalts and the overlying sedimentary succession are preserved. He referred the sediments to the Lower, Middle and Upper Series of the Kap Dalton Series and established the correct stratigraphic succession: the '*Cyrena* Beds' being the oldest and the '*Coeloma* Beds' the youngest (Fig. 3). The main part of his paper, however, was devoted to the petrology of the underlying basalt succession and alkaline basalt pebbles in a conglomerate found at the base of the sedimentary succession.

The sedimentary successions at Savoia Halvø (Kap Brewster) were discovered by D. Mackney and F.W. Sherrell during the Danish Expedition to East Greenland in 1951 (Hassan 1953). The sediments are preserved in a series of small grabens and were divided by Hassan (1953) into an Infra-Basalt unit below the lavas and the Kap Dalton and Kap Brewster Series above (Fig. 3). The Kap Dalton Series was further subdivided into the '*Cyrena* Beds' and '*Coeloma* Beds' following the established stratigraphy at the type locality. Based on macrofossils, Hassan (1953) assigned the Kap Brewster Series ('*Chlamys* Beds') to the Miocene.

Kap Dalton and Savoia Halvø were revisited by geologists in the 1960s and 1970s as part of a mapping campaign by the former Geological Survey of Greenland (GGU), and a formal lithostratigraphy was established. Based on field work at Savoia Halvø, Birkenmajer (1972) renamed the '*Cyrena* Beds' and '*Coeloma* Beds' originally defined at Kap Dalton as the Bopladsdalen and Krabbedalen Formations using geographical names from Savoia Halvø (Fig. 3). More importantly, however, new biostratigraphic data based on studies of dinoflagellate cysts and foraminifera considerably improved age constraints on the units (Birkenmajer 1972; Soper & Costa 1976; Soper *et al.* 1976; Birkenmajer & Jednorowska 1977, 1997).

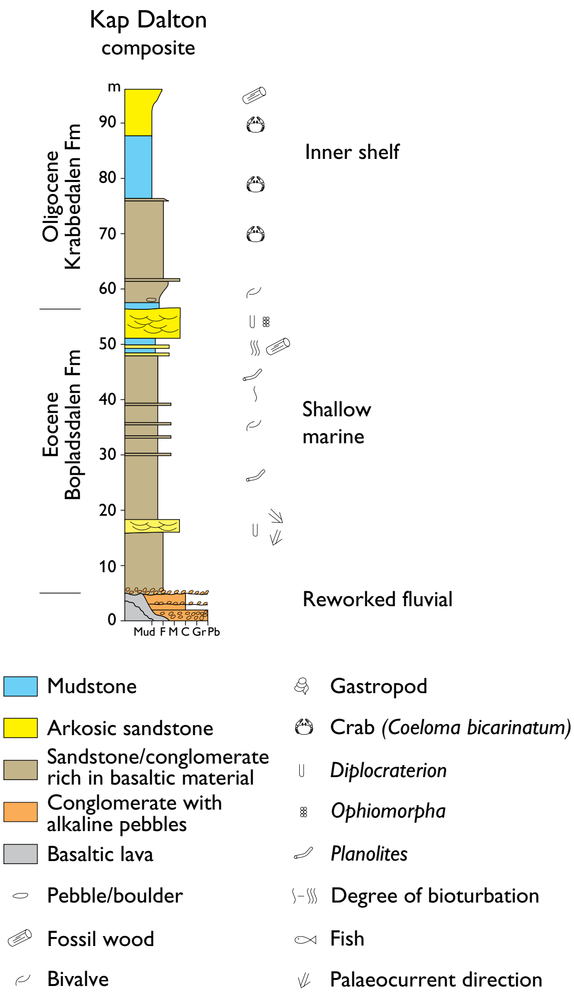

Fig. 4. Composite sedimentological profile of the Eocene–Oligocene succession at Kap Dalton.

Fig. 5. Concretions with perfectly preserved imprints of the crab *Coeloma bicarinatum* from the Oligocene Krabbedalen Formation at Kap Dalton. Concretion is 6 cm across.

Kap Dalton

Stratigraphy

The post-basaltic sedimentary succession at Kap Dalton consists of the lower, sandstone-dominated Bopladsdalen Formation and the upper, siltstone-dominated Krabbedalen Formation (Birkenmajer 1972; Birkenmajer & Jednorowska 1997). In the initial descriptions of the sediments at Kap Dalton the field relationships between the two formations were poorly constrained and both formations were believed to be of Early to Middle Eocene age based on macrofossils (Ravn 1904, 1933; Wager 1935). Later studies of dinoflagellate cyst assemblages confirmed an Early Eocene age of the Bopladsdalen Formation whereas the age of the Krabbedalen Formation was revised to the Oligocene (probably Early Oligocene) suggesting the presence of a hiatus at the formation boundary (Soper & Costa 1976; Soper *et al.* 1976).

Sedimentology

The sedimentary succession is generally poorly exposed and correlation is further hampered by later faulting. However, based on correlation of seven detailed sedimentary sections measured in 2001 it is possible to construct a composite profile, approximately 95 m thick, comprising the entire post-basaltic stratigraphy (Fig. 4).

The sediments rest unconformably on a weathered surface of subaerially extruded basalt flows of the Igtertivâ Formation (Larsen *et al.* 1989). The basal unit consists of a conglomerate, 2–3 m thick, with well-rounded basalt pebbles. The petrology of the pebbles was carefully examined by Wager (1935) who concluded that the assemblage contained an exotic suite of alkaline basalts not present anywhere else along the coast. The basal conglomerate is overlain by approximately 50 m of fine- to coarse-grained sandstones forming the bulk of the Bopladsdalen Formation. The succession consists mainly of poorly indurated brown and black sandstones rich in reworked basaltic material forming the '*Cyrena* Beds' (*sensu* Ravn 1904). However, yellowish, arkosic sandstones form distinct marker units at two stratigraphic levels. The yellow sandstones are slightly better cemented than the brown sandstones and show well-preserved sedimentary structures, mostly planar and trough cross-bedding indicating palaeocurrent directions towards the south and southeast. Locally, U-shaped vertical burrows of *Diplocraterion* and *Ophiomorpha* types are abundant. The bivalve *Cyrena* occurs in 10–30 cm thick beds of well-cemented, medium- to coarse-grained brown sandstone packed with disarticulated shells of *Cyrena* and scattered gastropods in the middle part of the succession.

The boundary between the Bopladsdalen and Krabbedalen Formations is marked by a change from coarse-grained, arkosic sandstones below to poorly consolidated, grey-brown, fine-grained sandstones above. The latter form the lower 20 m of the Krabbedalen Formation and are overlain by approximately 20 m of laminated, fine-grained sandstones and siltstones, carrying numerous concretions (the '*Coeloma* Beds' *sensu* Ravn 1904). With few exceptions the concretions contain perfectly preserved imprints of the crab *Coeloma bicarinatum* (Fig. 5).

Interpretation

The weathered surface of the basalts suggests a period of subaerial exposure prior to the onset of sedimentary deposition. The clast-supported conglomerate carrying well-rounded, exotic clasts is accordingly interpreted as laid down by a fluvial system transporting coarse erosional products from the volcanic hinterland. The fluvial channels were apparently restricted to topographic lows in the lava surface and the conglomerate is only very locally developed. During Early Eocene times the area was transgressed and the fluvial deposits and the adjacent basaltic surface were reworked. A thick shallow marine succession punctuated by at least two progradational events was deposited during the remaining part of Bopladsdalen Formation time. The top of the Bopladsdalen Formation is a distinct flooding surface reflecting a change towards deeper marine conditions. The frequent occurrence of small crabs and the general fine-grained lithology of the overlying Krabbedalen Formation suggest deposition in a low energy, possibly oxygen deficient environment. The interpretation of the entire post-basaltic succession as deposited during an overall transgression does not support the existence of a major hiatus at the boundary between the two formations as suggested by Soper & Costa (1976).

Savoia Halvø

Stratigraphy

The pre-basaltic sediments exposed on the north coast of Savoia Halvø adjacent to the former Kap Brewster settlement are described by Nøhr-Hansen & Piasecki (2002, this volume), and focus in this study is on the post-basaltic sediments of the Palaeogene Kap Dalton and the Neogene Kap Brewster Formations (Hassan 1953; Birkenmajer 1972). The Palaeogene sediments were divided by Hassan (1953) into the '*Cyrena* Beds' and '*Coeloma* Beds' following the stratigraphic scheme from Kap Dalton. Based on macrofossils the '*Cyrena* Beds' were interpreted to be of Late Eocene age, thus differing from the age assigned to the succession at Kap Dalton (Fig. 4; Ravn 1904, 1933). The overlying '*Coeloma* Beds' were suggested to be of Early Oligocene age at Savoia Halvø, thus following conformably upon the '*Cyrena* Beds'. An Early Oligocene age was supported by the foraminifer assemblage described by Birkenmajer (1972) and Birkenmajer & Jednorowska (1977, 1997). In their publications Birkenmajer & Jednorowska presented a revised stratigraphic scheme changing the age of the Bopladsdalen Formation to Early Eocene (Fig. 4), but this new interpretation was not discussed nor supported by new data.

The Neogene Kap Brewster Formation ('*Chlamys* Beds' *sensu* Hassan 1953) was thought to be of Miocene age based on the macrofossils, although Hassan (1953) stressed that this age was to be regarded as tentative until supported or revised by further evidence. Unfortunately, no such evidence has yet come to light and the presumed Miocene age of the Kap Brewster Formation has still to be confirmed.

Sedimentology

The sediments on Savoia Halvø are exposed along the river flowing east and north through the valleys Krabbedalen and Bopladsdalen (Fig. 6). The sandstone-dominated Bopladsdalen Formation, 90 m thick, and the lower part of the mudstone-dominated Krabbedalen Formation, 40 m thick, are exposed in a continuous outcrop (Fig. 7A). The approximately 110 m thick conglomeratic Kap Brewster Formation is limited to an isolated outcrop at Muslingehjørnet some 1–2 km further to the north, and cannot be correlated with the other post-basaltic units on field criteria.

The sediments of the Bopladsdalen Formation unconformably overlie a weathered surface of basalts with pillow structures. The lowermost unit is 1–2 m thick and consists of a matrix-supported conglomerate carrying well-rounded basaltic boulders. The conglomerate is overlain by a thick sandstone-dominated succession showing a general fining-upward trend (Fig. 7A). In the lower part numerous incursions of coarse-grained material of angular basalt pebbles are concentrated in erosional layers and elongate lenses showing normal grading. Bivalve shell material is locally present on bedding surfaces. Higher in the succession silicified tree trunks, up to 5 m long, are interbedded within fine- to medium-grained sandstones. Associated with the silicified trees are large isolated boulders of well-rounded basalt. Bioturbation is present throughout the succession although diagenetic alteration of the sandstone locally hinders recognition of sedimentary and biogenetic structures. The boundary with the overlying Krabbedalen Formation is placed at the first distinctive mudstone bed (Fig. 7A). The latter formation consists of alternating beds of laminated siltstone and massive fine-grained sandstones. Large calcareous concretions are present throughout the succession and like the similar concretions in the formation at Kap Dalton contain imprints of the crab *Coeloma bicarinatum* in two discrete horizons in the middle part. The concretions also contain fragments of bivalves, gastropods, silicified wood and in one case part of a fish spine.

The conglomerates of the Kap Brewster Formation are preserved in the hanging-wall block immediately south of a major NE–SW-trending normal fault. Neither the base nor top of the formation is exposed, and the relationships to the basalts and the other post-basaltic sediments are not known. The succession can be divided into three distinct units with a middle sandstone unit separating a lower and an upper conglomeratic unit (Fig. 7B). The lower unit is approximately 40 m thick, and consists of stacked, matrix-supported conglomerate beds, up to 5 m thick, carrying well-rounded basaltic boulders up to 1.5 m in diameter. The matrix varies in grain-size from poorly sorted, gravelly mudstones to pebbly sandstones. Most of the beds show a crude fining-upward trend in clast size. The stacked conglomerates are overlain by poorly exposed basaltic sandstones forming the middle unit, up to 45 m thick (Fig. 7B). Locally, exposures allow recognition of ripple cross-laminated, pebbly sandstone beds, up to 20 cm thick. These beds are rich in fragmented oysters and other bivalves. The sandstones are overlain by matrix-supported boulder conglomerates of the upper unit reaching up to 25 m in thickness.

Fig. 6. Eocene sandstones of the Bopladsdalen Formation exposed at Savoia Halvø. The river bank is approximately 35 m high.

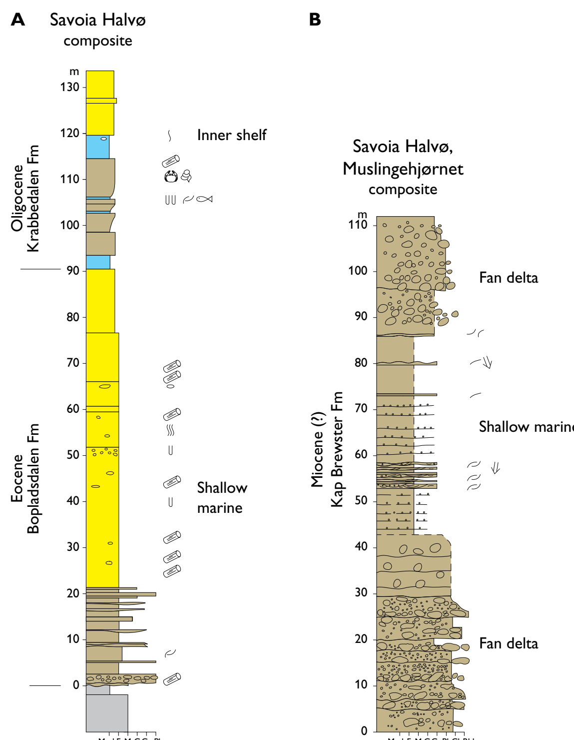

Fig. 7. Composite sedimentological profiles of the Palaeogene and ?Neogene successions at Savoia Halvø. **A**: Bopladsdalen and Krabbedalen Formations measured along the river flowing through Krabbedalen. **B**: Kap Brewster Formation measured at Muslingehjørnet (see Fig. 1A for locations and Fig. 4 for legend).

Interpretation

The pillow structures present in the basalts immediately below the Bopladsdalen Formation suggest that the uppermost preserved lavas were extruded below water. However, the weathered zone forming the transition to the sediments indicates a period of uplift and subaerial exposure prior to the start of deposition. The rounded boulders in the basal conglomerate of the Bopladsdalen Formation were probably locally derived, and may have been rounded either during current or wave action. The few diagnostic structures in the overlying overall fining-upward succession suggest that deposition took place in a shallow marine environment. The frequent scour-and-fill and the graded beds present in the lower part suggest deposition close to storm-wave base, possibly close to the mouth of a major river system in view of the abundant tree trunks. A continued rise in the relative sea level is indicated by a decrease in the amount of coarse-grained material and wood, and deposition of fine-grained sand and mud of the Krabbedalen Formation in Early Oligocene time.

The matrix-supported conglomerates of the Kap Brewster Formation were probably deposited by gravity flow processes in a marine fan-delta. The tripartite upbuilding suggests at least two progradational pulses leading to gradual fining-upward successions. Although the stratigraphical data are sparse and the field relationships with the other post-basaltic sediments are unknown, the lithological resemblance between the fine-grained parts of the Kap Brewster Formation and the lower part of the Bopladsdalen Formation is striking, and the two formations may represent different parts of the same depositional basin rather than two distinct depositional events.

Future work

The 2001 season concluded the geological field work in the pre- and early post-basaltic sedimentary successions along the Blosseville Kyst initiated in 1995 with field work in Kangerlussuaq in the southern part (Larsen *et al.* 1996, 2001). Future work will focus on the litho-, bio- and sequence-stratigraphy. Based on the accumulated knowledge, the basin evolution and uplift history of the northern North Atlantic during Palaeogene time will be evaluated.

Following the 2001 field work the sample database at GEUS comprises more than 600 samples covering all lithologies and formations from the Cretaceous–Palaeogene successions of southern and central East Greenland. Mudstones and fine-grained sandstones sampled for palynological work will be analysed at the Geological Institute, University of Aarhus and at GEUS. Based on field observations, two units at Kap Dalton having a distinct arkosic composition will be examined petrographically and geochemically in order to define their provenance areas. The results of this work will be reported elsewhere. A revised lithostratigraphy will be proposed based on the new lithological, sedimentological and palynological data.

Conclusions

1. The post-basaltic successions rest on a deeply weathered basaltic surface that at Kap Dalton dips southeastwards.

2. At Kap Dalton the basal conglomerates consist of alkaline basaltic pebbles most likely transported in fluvial channels from a westerly source, whereas the remaining part of the post-basaltic succession was deposited in a shallow marine environment.

3. Material from at least three different source areas is present in the successions: (1) alkaline pebbles, (2) siliciclastic sand, (3) sand rich in reworked basaltic material. Of these, only the latter was locally derived. The source area of the alkaline pebbles is unknown, whereas the siliciclastic sand was probably derived from exhumed basement areas to the north-east.

4. Sedimentological data from Savoia Halvø suggest that the Kap Dalton and Kap Brewster Formations may form proximal–distal correlatives of the same depositional system in this area. Biostratigraphic data are, however, needed in order to confirm this interpretation.

Acknowledgements

The field work was part of the Survey's studies in stratigraphy, sedimentology and basin evolution in Greenland and the northern North Atlantic. The helicopter programme and general logistics in East Greenland were co-ordinated by T.I. Hauge Andersson (Danish Polar Center).

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *mil@geus.dk*

Paleocene sub-basaltic sediments on Savoia Halvø, East Greenland

Henrik Nøhr-Hansen and Stefan Piasecki

Field work by the Geological Survey of Denmark and Greenland (GEUS) on Savoia Halvø, central East Greenland in 2001 (see also Larsen *et al.* 2002, this volume) included a study of sediments underlying the Palaeogene basalts on the south coast of Scoresby Sund (Fig. 1). The importance of this small exposure is based on the fact that it provides one of the few opportunities for establishing a marine biostratigraphic date for the sediments below the basalts. Dinoflagellate cysts from the sediments provide a maximum Early Paleocene age for the onset of the volcanism in central East Greenland. Reports from previous field work have mentioned the sediments (Hassan 1953; Birkenmajer 1972), but no precise age assignment was presented due to the absence of diagnostic fossils. The sub-volcanic sediments of Savoia Halvø represent the youngest preserved marine sedimentary deposits of the Upper Palaeozoic – Cenozoic rift-basins onshore East Greenland. The overlying Palaeogene flood basalts occasionally contain very thin sedimentary beds between the lava flows, but these were deposited above sea level. Neogene uplift of the East Greenland margin brought a definitive end to accumulation in the old sedimentary basins (Watt *et al.* 1986; Christiansen *et al.* 1992).

Geology

South of Scoresby Sund (70°N), the Palaeozoic–Cenozoic rift basins of East Greenland are concealed by thick and extensive continental flood basalts of Palaeogene age. The basalts extend uninterrupted for more than 200 km towards the south (*c.* 68°N). North of Scoresby Sund an irregular sub-basaltic peneplain rises above sea level and basalt outliers cap the mountains on Milne Land and areas to the west (Watt *et al.* 1986). A second, less extensive area of Palaeogene basalts occurs further north in North-East Greenland in the Hold with Hope – Clavering Ø region (Fig. 1).

In the Scoresby Sund region the earliest basalts unconformably overlie Caledonian crystalline gneisses and Mesozoic–Palaeogene sedimentary rocks. The earliest flows erupted into palaeovalleys locally developed as hyaloclastic deposits indicative of extrusion into lakes, but pene-contemporaneous marine sediments are only known to crop out at one locality on Savoia Halvø, adjacent to the Kap Brewster settlement (Fig. 1). Elsewhere in East Greenland, contemporaneous sub-basaltic terrestrial sediments are known *c.* 450 km to the north on Clavering Ø and Hold with Hope but have not yet yielded any clear indication of their age. About 250 km towards the south (*c.* 68°N) in the Kangerlussuaq region the earliest volcanics are associated with terrestrial to marginal marine sedimentary deposits.

The Kap Brewster locality

Adjacent to the abandoned Kap Brewster settlement (Fig. 1), the almost vertical basalt cliffs are 200–1000 m high. To the west of the settlement, steep scree-slopes of large basalt blocks at the foot of the cliffs are partly covered by permanent ice and snow. To the east, the valley Bopladsdalen provides easy access to the plateau on southern Savoia Halvø where down-faulted, post-basaltic sediments crop out (Bopladsdalen, Krabbedalen and Kap Brewster Formations; Fig. 1; see Larsen *et al.* 2002, this volume). The Kap Brewster houses are situated on a narrow beach just west of the entrance to Bopladsdalen, and the first *in situ* sediments appear 50 m up the cliff behind the houses. Approximately 40 m of poorly exposed, dark grey, bioturbated mudstone occurs between 50 and 90 m above sea level (Larsen *et al.* 2002, this volume). Except for imprints of spatangid echinoderms (Hassan 1953) no macro-fossils have been reported from the mudstone, but dinoflagellate cysts have been mentioned (Watt & Watt 1983; Larsen & Marcussen 1992). The contact between sediments and the lowest basalt flow, at approximately 91 m, is not exposed; the lowest outcrop of volcanic rocks is a volcanic conglomerate about 50 m to the east.

Thirteen samples from the uppermost 40 m of the mudstone were analysed for dinoflagellates; the highest

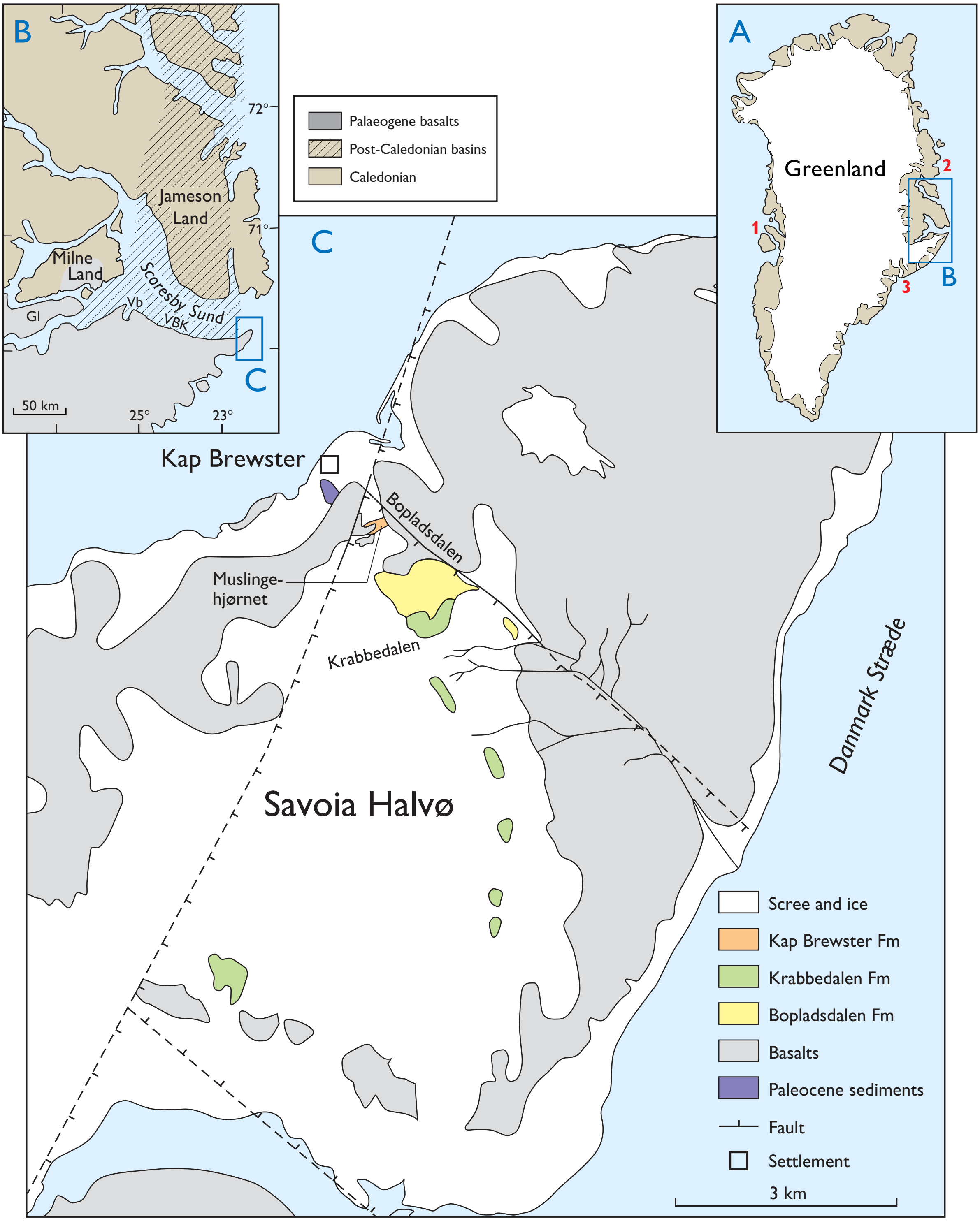

Fig. 1. Map of East Greenland with a simplified geological map of Savoia Halvø based on Birkenmajer (1972, fig. 1). The locality with exposed sub-basaltic sediments is situated adjacent to the Kap Brewster settlement. Inset **A**: Greenland map; **1**: West Greenland, Nuussuaq; **2**: North-East Greenland, Wollaston Forland – Hold with Hope – Clavering Ø region; **3**: East Greenland, Kangerlussuaq region. Inset **B**: **VBK**: Volquart Boon Kyst; **Vb**: Vikingebugt; **Gl**: Gåseland.

sample was taken 1 m below the first basalt flow. The samples were prepared by standard palynological techniques with HCl and HF. The organic residue was oxidised with HNO_3, and the microscopic fossils were separated from the terrestrial debris by swirling or the tube separation method of Hansen & Gudmundsson (1979).

Marine flora

Moderately to well-preserved dinoflagellate cysts are abundant in the mudstone together with an abundance of terrestrial organic material, spores and pollen. All analysed samples contain a rich dinoflagellate flora composed of a mixture of reworked Lower to Upper Cretaceous dinoflagellate cyst assemblages, together with Paleocene marker species.

Cretaceous dinoflagellate cysts

Stratigraphically significant dinoflagellate cysts in the composite assemblage suggest reworking from multiple sources of Cretaceous sediments or perhaps repeated reworking of Cretaceous dinoflagellate assemblages. Cretaceous dinoflagellate assemblages in East Greenland have been described by Nøhr-Hansen (1993), and mid-Cretaceous to Paleocene dinoflagellate assemblages have been described from corresponding latitudes in West Greenland (Nøhr-Hansen 1996; Nøhr-Hansen *et al.* in press).

The presence of *Leptodinium cancelatum* and *Pseudoceratium expolitum* indicates reworking from middle Albian (Lower Cretaceous) strata according to Nøhr-Hansen (1993). *Epelidosphaeridia spinosa*, *Hapsocysta benteae*, *Ovoidinium* sp. 1 Nøhr-Hansen 1993, *Rhombodinium paucispina* and *Subtilisphaera kalaalliti* indicate reworking from Upper Albian to Lower Cenomanian strata (Nøhr-Hansen 1993). *Chatangiella* spp. and *Isabelidinium* spp. suggest reworking from Upper Cenomanian to Upper Maastrichtian (Upper Cretaceous) strata, and the presence of the pollen genus *Aquilapollenites* spp. indicates reworking from Campanian to Upper Maastrichtian strata (Upper Cretaceous) according to Nøhr-Hansen (1996). The possibility that even Paleocene strata could be reworked is indicated by the presence of a few *Spongodinium delitiense* which have a range from Campanian to lower Danian, Paleocene (Hardenbol *et al.* 1998). These reworked Cretaceous assemblages are very similar to the assemblages described from North-East Greenland (Nøhr-Hansen 1993) and West Greenland (Nøhr-Hansen 1996).

Paleocene dinoflagellate cysts

Paleocene dinoflagellate cysts are rare to very rare and are generally poorly preserved, but occur in all studied samples (Fig. 2). Poorly preserved *Alisocysta* spp. (probably *A. margarita*; Fig. 3a–c) occurs together with *Areoligera* spp. (Fig. 3d–e), *Cerodinium striatum* (Fig. 3g–h) and *Palaeoperidinium pyrophorum* throughout the studied section whereas *Phelodinium kozlowskii* (Fig. 3i), *Palaeocystodinium bulliforme* (Fig. 3j–k), *Spiniferites septatus* (Fig. 3f) and *Thalassiphora delicata* (Fig. 3l) are restricted to the upper part.

The presence of probable *Alisocysta margarita* suggests a late Danian (61.58 Ma) to early Thanetian (57.16 Ma) age (Hardenbol *et al.* 1998), but according to the same authors the presence of *Palaeocystodinium bulliforme* and *Palaeoperidinium pyrophorum* excludes

Kap Brewster

Age		Metres above sea level	GGU sample numbers	*Areoligera* spp.	*Cerodinium striatum*	*Palaeoperidinium pyrophorum*	*Alisocysta margarita*	*Spiniferites septatus*	*Areoligera* aff. *gippingensis*	*Cerodinium* spp.	*Palaeocystodinium bulliforme*	*Phelodinium kozlowskii*	*Thalassiphora delicata*
Paleocene	early Selandian ?	90	246950	+	+	+	+	+	+	+	+	+	
			246949		+	+	+			+			+
			246948			+	+		+	+	+		
			246947	+		+				+	+	+	
			246946	+	+	+					+		
		80	246945			+			+	+			
			246944	+	+	+		+					
			246943	+	+	+	+	+	+				
			246942		+	+	+	+	+	+	+	+	+
	late Danian		246941	+		+	+	+	+	+			
		70	246940	+		+	+	+	+	+	+		
			459739	+	+			+					
		60											
		50	459738	+	+	+	+						

Fig. 2. Stratigraphic occurrence of selected *in situ* Paleocene dinoflagellate cysts in pre-basaltic mudstones at Kap Brewster.

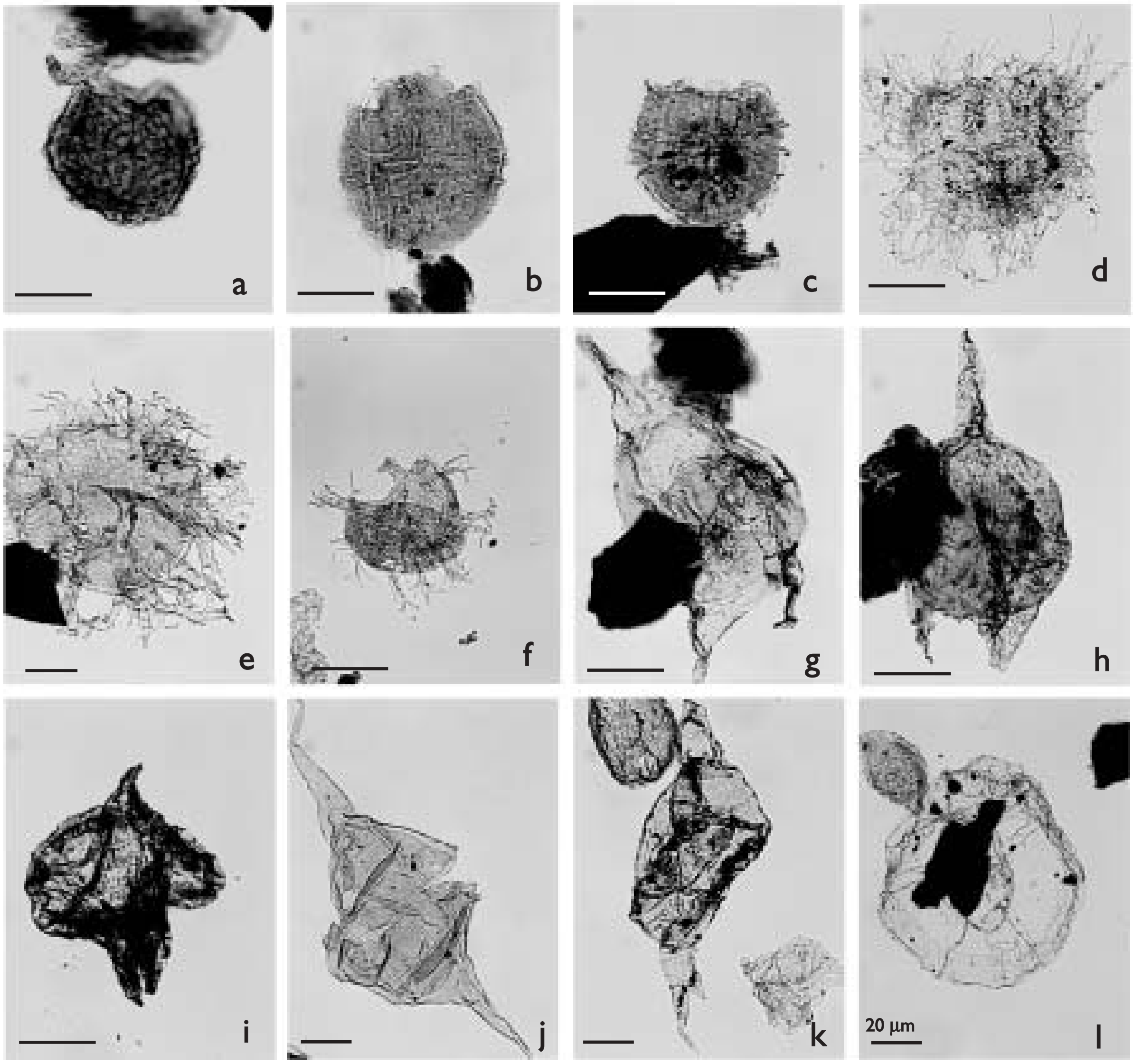

Fig. 3. Stratigraphically important dinoflagellate cysts. The scale bars represent 20 µm. GGU numbers identify the samples, followed by preparation-slide number and the co-ordinates of the microscope table. MI and LVR numbers identify records in the MicroImage database. The illustrated specimens are deposited in the type collection of the Geological Museum, University of Copenhagen and are identified by the MGUH number.

a: *Alisocysta margarita*, GGU 459738-4, 37.0–102.5, MI 11762, LVR 1.23519, MGUH 26.391.

b: *Alisocysta margarita*, GGU 246940-13, 33.2–108.2, MI 11728, LVR 1.23439, MGUH 26.392.

c: *Alisocysta margarita*, GGU 246940-12, 28.5–112.2, MI 11729, LVR 1.23440, MGUH 26.393.

d: *Areoligera* spp., GGU 246940-12, 31.5–103.0, MI 11730, LVR 1.23441, MGUH 26.394.

e: *Areoligera* spp., GGU 246945-7, 43.0–108.6, MI 11735, LVR 1.23451, MGUH 26.395.

f: *Spiniferites septatus*, GGU 246943-4, 33.7–106.4, MI 11733, LVR 1.23447, MGUH 26.396.

g: *Cerodinium speciosum*, GGU 246946-7, 27.0–109.0, MI 11736, LVR 1.23452, MGUH 26.397.

h: *Cerodinium striatum*, GGU 246943-4, 20.3–100.5, MI 11740, LVR 1.23456, MGUH 26.398.

i: *Phelodinium kozlowskii*, GGU 246942-4, 39.6–111.6, MI 11741, LVR 1.23457, MGUH 26.399.

j: *Palaeocystodinium bulliforme*, GGU 246950-4, 38.7–109.3, MI 11739, LVR 1.23455, MGUH 26.400.

k: *Palaeocystodinium bulliforme*, GGU 246947-8, 29.5–95.0, MI 11738, LVR 1.23454, MGUH 26.401.

l: *Thalassiphora delicata*, GGU 246949-7, 36.4–93.9, MI 11737, LVR 1.23453, MGUH 26.402.

Thanetian and suggests an age no younger than late Selandian (58.04 Ma). The first occurrence of *Thalassiphora delicata* in the upper part of the succession suggests an early Selandian or younger age for this part of the section according to Thomsen & Heilmann-Clausen (1985) although Köthe (1990) recorded rare *T. delicata* from the latest Danian in Germany.

Therefore, it can be concluded that the dinoflagellate assemblage indicates a late Danian age for the lower part (50–72 m) and a late Danian – early Selandian? age for the upper part (74–90 m) of the succession, based on correlations with North-West Europe (Köthe 1990; Powell 1992) and West Greenland (Nøhr-Hansen *et al.* in press).

Geological implications

The axis of the Mesozoic Jameson Land basin dips southwards below the fjord of Scoresby Sund. Seismic lines in the fjord reveal sediments intruded by numerous sills and dykes such that stratigraphical correlation with the onshore succession on Jameson Land is difficult; however, sediments younger than the topmost, Lower Cretaceous succession of Jameson Land are known to occur below the basalts (Larsen & Marcussen 1992). Seismic data along Volquart Boon Kyst show that the base of the basalt succession reaches 500 m below sea level in the central part of the basin (Larsen & Marcussen 1992) but gradually approaches sea level towards the basin margins (i.e. at Kap Brewster in the east and Vikingebugt–Gåseland in the west; Fig. 1B). Pre-basaltic erosion planed off basinal areas of sediments between highs of crystalline rocks of the basin margins (Larsen *et al.* 1989). In Gåseland and Milne Land basalts rest on Jurassic sediments and in the central part of the basin on presumed Upper Cretaceous – Paleocene sediments which provide a maximum age for the overlying volcanic rocks.

On Savoia Halvø near the Kap Brewster settlement the base of the basalts comprises the basal Milne Land Formation (Larsen *et al.* 1989; L.M. Larsen, personal communication 2002). Observations at the Kap Brewster locality and seismic data from the central Jameson Land basin (Larsen & Marcussen 1992) suggest that the basalts are conformable with the youngest sedimentary unit. Correlation of the extended Milne Land Formation (includes the earlier Magga Dan Formation; L.M. Larsen, personal communication 2002) with the lowermost Middle Series of the Faeroe Islands basalt succession indicates equivalence to lower Chron 24R, latest Paleocene age, 55 Ma (Larsen *et al.* 1999). However, the onset of volcanism in East Greenland as recorded from boreholes offshore South-East Greenland (Sinton & Duncan 1998) and onshore in the Kangerlussuaq region occurred at maximum 61–62 Ma, corresponding to Chron 27N of latest Danian, Early Paleocene (Hansen *et al.* in press). The latter is contemporaneous with the earliest West Greenland volcanic rocks (60–61 Ma; Storey *et al.* 1998) whereas the proposed correlation of the East Greenland flood basalts (e.g. at Kap Brewster) with a second, younger magmatic phase in West Greenland at approximately 55–52.5 Ma is more speculative.

The dark mudstones below the basalts at Kap Brewster have previously been considered Cretaceous on the basis of screening of dinoflagellate assemblages (Watt & Watt 1983; Larsen & Marcussen 1992), and indeed the sediments are rich in well-preserved but reworked Cretaceous dinoflagellate cysts. However, the new dinoflagellate flora described above clearly indicates a late Danian – early Selandian? (Paleocene) age for these mudstones, i.e. significantly older than the overlying basalts. It can be surmised that a distinct hiatus corresponding to most of the Upper Paleocene separates the mudstone from the overlying basalts. This hiatus may reflect either pre-basaltic erosion of the basin margin (e.g. at Kap Brewster) or a basal unconformity, even though there is an apparent seismic conformity of basalts and the youngest sediments in the central part of the basin.

Conclusions

No sedimentary successions from which the distinctly reworked dinoflagellate Cretaceous assemblages were derived are known in the onshore outcrops of the Jameson Land basin in the Scoresby Sund region, although corresponding strata may be represented in the offshore Lower Cretaceous – Paleocene succession beneath Scoresby Sund.

The *in situ* Paleocene dinoflagellate cyst assemblage can be correlated with Paleocene assemblages from the uppermost pre-volcanic sedimentary successions known onshore Nuussuaq in West Greenland (Nøhr-Hansen *et al.* in press), and corresponds in age to the upper, marine part of the Ryberg Formation in the Kangerlussuaq region (Soper *et al.* 1976).

The latest Danian – early Selandian? (Paleocene) age of the youngest pre-basaltic sediments both in West Greenland and in the Kangerlussuaq region (East Greenland) corresponds to the age of the earliest volcanic rocks in these regions. The biostratigraphic age is also in agreement with the radiometric age of the earliest eruptives offshore South-East Greenland, onshore at Kangerlussuaq (East Greenland) and in West Greenland. In contrast, a significant hiatus separates the Danian – lowermost Selandian? sediments from the uppermost Paleocene – Lower Eocene volcanics at Kap Brewster.

Acknowledgements

The work is part of the Survey's programme of studies in stratigraphy, sedimentology and basin evolution in Greenland and the northern North Atlantic.

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *hnh@geus.dk*

Lower–Middle Ordovician stratigraphy of North-East Greenland

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

The Upper Proterozoic (Riphean) to Lower Palaeozoic succession in North-East Greenland is exposed in a broad N–S-trending belt in the fjord region between 71°38´ and 74°25´N (Fig. 1). The succession comprises mainly marine sediments accumulated during the later stages of the break-up of the Rodinia supercontinent, the subsequent opening of the Iapetus Ocean and formation of the passive margin along the edge of the Laurentian palaeocontinent.

Investigations of the sedimentary succession were initiated on Ella Ø in the summer of 2000 as part of a project to investigate the development of the Laurentian margin facing the Iapetus Ocean in the Early Palaeozoic, when studies of the uppermost formations of the Riphean Eleonore Bay Supergroup to the Lower Ordovician Antiklinalbugt Formation on Ella Ø were undertaken (Stouge *et al*. 2001). Ella Ø was revisited during the summer of 2001, with the focus on the Ordovician formations. In addition, investigations were undertaken in the Albert Heim Bjerge area where the uppermost part of the Ordovician succession is preserved (Fig. 1).

The scientific station at Solitærbugt on Ella Ø (Fig. 1) was used as the operational base, and helicopter support allowed the establishment of camps on the plateau of Ella Ø and in the Albert Heim Bjerge area.

Ella Ø

Ella Ø preserves exposures of the uppermost part of the Riphean Eleonore Bay Supergroup and the whole of the Vendian Tillite Group, while the Lower Palaeozoic sequence ranges from the Lower Cambrian to the lower Middle Ordovician (Fig. 2; Poulsen 1930; Poulsen & Rasmussen 1951; Cowie & Adams 1957; Hambrey 1989). This succession is unconformably overlain by Devonian continental aeolian and fluviatile clastic rocks.

The main aims of the work on Ella Ø in 2001 were to carry out detailed stratigraphic logging of the upper Lower Ordovician Cape Weber Formation and the lower Middle Ordovician Narwhale Sound Formation, to collect samples for biostratigraphical control throughout the succession in order to constrain the duration of the major hiatus recorded in the Lower Ordovician part of the succession, and to define the lithological boundaries between the recognised units.

Excellent exposures of the Lower to Middle Ordovician strata are found on the 500–900 m high central plateau of Ella Ø (Fig. 1, section 4; Fig. 3) and along the steep cliffs around Antiklinalbugt (Fig. 1, section 5; Fig. 4) which were reached from the base camp using a rubber dinghy.

The overall succession through the stratigraphic interval of the upper Canadian Series (Lower Ordovician) and into the lower Whiterockian (Middle Ordovician) is a conformable, shallowing-upward carbonate succession that begins disconformably above the silty, dolomitic beds forming the top of the Antiklinalbugt Formation (Figs 2, 4).

Cape Weber Formation

The basal contact of the Cape Weber Formation is placed at the top of the dolomitic beds mentioned above. The upper boundary of the Cape Weber Formation is placed at the appearance of the finely laminated, light grey, yellow-weathering dolostone and dolomitic limestone of the overlying Narwhale Sound Formation.

Cowie & Adams (1957) subdivided the Cape Weber Formation on Ella Ø into a lower 'Banded Limestones', the 'Main Limestones' and the upper 'Dolomites and Dolomitic Limestones'. In this study the formation has been measured to be 1140 m thick on Ella Ø, and four informal mappable lithological units are distinguished: units A–D. Unit A and the lower part of Unit B correspond to the 'Banded Limestones', Unit C is equivalent to the 'Main Limestones' and Unit D comprises the upper part of the 'Main Limestones' and the 'Dolomites and Dolomitic Limestones' of Cowie & Adams (1957).

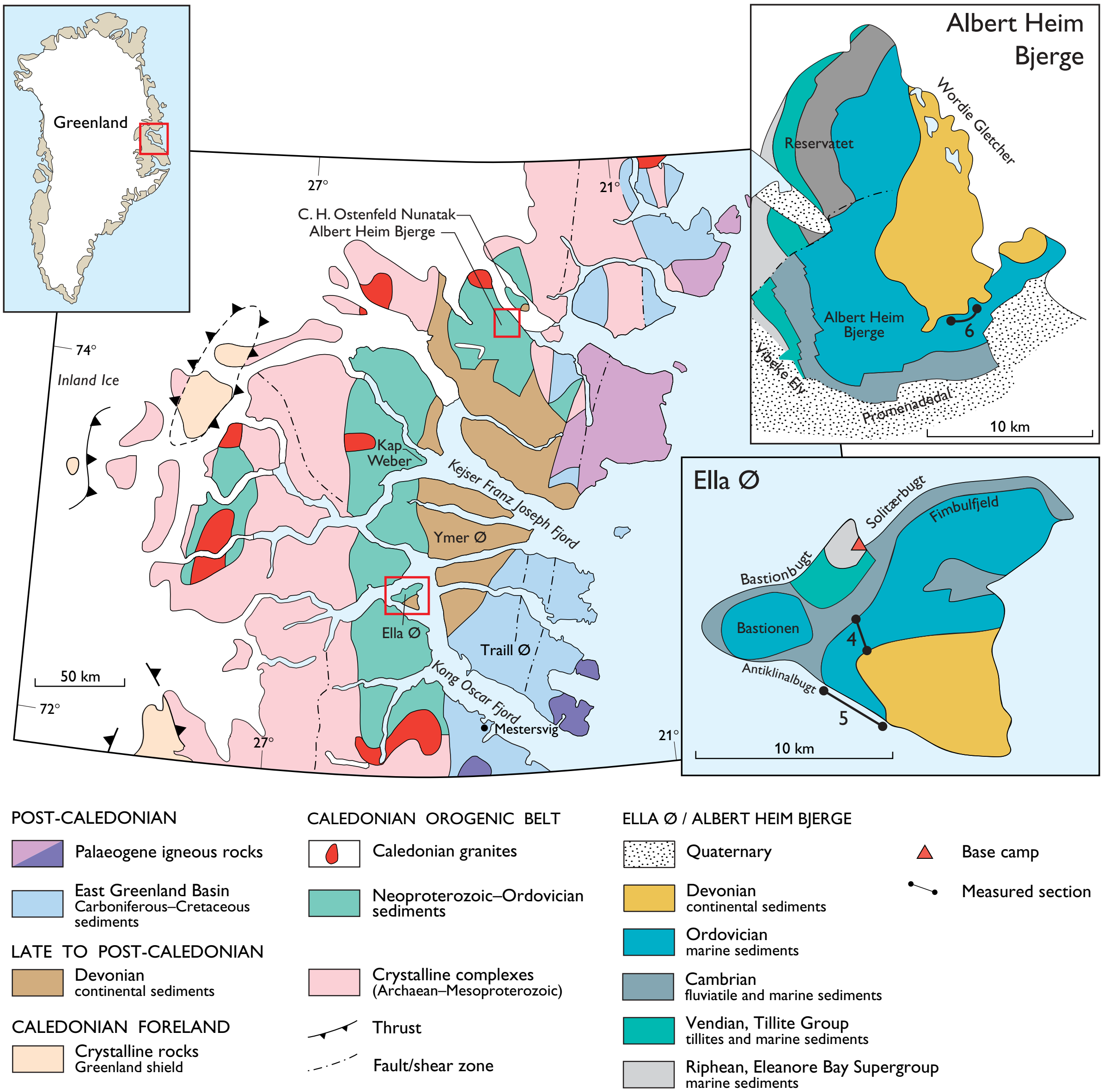

Fig. 1. Locality map of North-East Greenland with simplified geology. The inset maps of Ella Ø and Albert Heim Bjerge show locations of the investigated sections 4, 5 and 6. Geology modified from Cowie & Adams (1957) and Henriksen (1999).

Unit A

Unit A is 100 m thick. The sequence is made up of metre-thick carbonate beds composed of domal to broad, flat stromatolitic and thrombolitic mounds (Fig. 5), laminated lime mudstone and dolostone, intraclastic limestones, minor chert nodules and white-weathering silty interbeds.

The macrofauna recorded from the unit includes trilobites, cephalopods and gastropods. The lower interval is characterised by the trilobite *Peltabellia* sp. whereas the higher part of Unit A is referred to the *Strigigenalis brevicauda* Zone (Boyce 1989; Boyce & Stouge 1997). These two faunal intervals represent the Jeffersonian Stage of the Canadian Series. The sparse conodont fauna (Smith 1991) is included in the comprehensive Fauna D of Ethington & Clark (1971). Smith (1991) had

System	North America			Ibex-Utah, USA	W. Newfoundland	North-East Greenland		
	Series		Stage	Trilobite zones Ross (1951); Hintze (1953, 1973)	Trilobite zones Boyce & Stouge (1997)	Formations informal units Albert Heim Bjerge	Ella Ø	
Ordovician	Middle	Whiterockian		O – L	(Not zoned)	Heimbjerge	Hiatus	
						Narwhale Sound	Narwhale Sound	
	Lower	Canadian	Cassinian	J I H	*Benthamaspis gibberula*	Cape Weber	Cape Weber	Unit D
								Unit C
					Strigigenalis caudata			Unit B
			Jeffersonian	G	*Strigigenalis brevicaudata*			Unit A
					(*'Peltabellia* sp.')			
			Demingian	E/F	*Randaynia saundersi*	?	Hiatus	
			Gasconadian	B	*Symphysurina*	Antiklinalbugt	Antiklinalbugt	

Fig. 2. The upper Lower to Middle Ordovician stratigraphy of North-East Greenland compared to trilobite zones of Utah, USA and western Newfoundland, Canada.

Fig. 3. Plateau of Ella Ø showing the lower part of section 4 looking north-east. The banded unit to the left is Unit B, which is succeeded by Unit C. Camp (in circle) for scale.

placed the lowermost *c.* 50 m of his Cape Weber Formation within the *Rossodus manitouensis* Zone, which is Tremadoc (Gasconadian–Demingian) in age. However, this packet of carbonate sediments occurs below the extensive disconformity recognised by Stouge *et al.* (2001; Fig. 2), and on lithological criteria these older sediments are better placed within the Antiklinalbugt Formation.

Unit B

Unit B is 250 m thick. The lower part consists of peritidal cycles composed of well-bedded bioturbated and stylonodular limestones, thrombolitic mounds and thinly bedded, laminated dolomitic limestones; ostracodes and trilobites are recorded. The upper part of Unit B is characterised by bedded, bioturbated and peloidal limestones, mounds and abundant brown-weathering chert nodules. The chert nodules are stratabound and richly fossiliferous; coiled and straight cephalopods are common.

The lower part of Unit B belongs to the conodont Fauna D of Ethington & Clark (1971), whereas the upper cherty part of Unit B is included in the *Oepikodus communis* Zone (Smith 1991; Boyce & Stouge 1997). The *Strigigenalis brevicaudata* trilobite zone extends into the lower portion of Unit B, whereas the upper part of the unit is in the *Strigigenalis caudata* Zone.

Unit C

Unit C is 330 m thick and composed of thick-bedded, grey to dark grey peloidal and bioturbated packstone

Fig. 5. Stromatolite and thrombolite mounds from Unit A, Cape Weber Formation, Ella Ø.

Fig. 4. Section 5 in Antiklinalbugt on the southern side of Ella Ø. Devonian clastic rocks at right unconformably overlie the Middle Ordovician Narwhale Sound Formation.
A: Antiklinalbugt Formation
CW: Cape Weber Formation
NS: Narwhale Sound Formation
D: Devonian
T: 1047 m above sea level

to grainstone associated with mounds and closely spaced, stratabound nodular chert. The macrofauna is rich and varied and often silicified. Faunal elements include brachiopods, trilobites, gastropods, cephalopods, crinoids and sessile *insertae sedis*, possibly representative of sponges. The trilobite fauna indicates equivalence with the *S. caudata* Zone or perhaps the *Benthamaspis gibberula* Zone. The conodont fauna is sparse and corresponds to the upper part of the *O. communis* Zone (Smith 1991; Boyce & Stouge 1997).

Unit D

Unit D, about 460 m thick, is composed of grey lime mudstone and peloidal limestone, dark bituminous mudstone and peloidal, thickly bedded, bioturbated carbonates with minor dolomitic horizons containing chert. A characteristic marker bed about 100 m from the top of the unit is composed of thrombolites and stromatolites with grainstone intrabeds. The marker horizon is overlain by medium-bedded wackestone and peloidal lime mudstones and dolomitic bioturbated limestone associated with chert. The macrofauna is highly diverse and rich below the local marker horizon, and cephalopods are common (Fig. 6). The trilobites are assigned to the *Benthamaspis gibberula* Zone, which is coeval with Zones H and I *sensu* Ross (1951) and Hintze (1953, 1973) of the Utah–Nevada sections (Boyce & Stouge 1997). It is possible, however, that Unit D may be as young as Zone J (= *Pseudocybele nasuta* Zone of Fortey & Droser 1996) of the Utah–Nevada successions. The conodont fauna (Stouge 1978; Smith 1991)

Fig. 6. Straight silicified cephalopod from Unit D, Cape Weber Formation, Ella Ø.

is abundant and highly diverse, and is referred to the *Jumodontus gananda – ?Reutterodus andinus* Interval of Ethington & Clark (1981). In the uppermost 100 m of the unit (above the grainstone marker horizon) the conodont fauna is, however, of low diversity and not biostratigraphically distinctive (Smith 1991).

Narwhale Sound Formation

On Ella Ø the Narwhale Sound Formation was only studied in section 4 (Fig. 1); in section 5 many closely spaced and nearly coast-parallel faults disrupt the succession. The sediments comprise sucrosic dolostones with a vuggy texture, and no original sedimentary structures are preserved.

The base of the Narwhale Sound Formation is recorded as a prominent 7 m thick bed of laminated and cross-bedded dolostone and dolomitic bioturbated limestone. The remainder of the 260 m thick succession consists of pale grey to cream grey microcrystalline to sucrosic dolostone, pale grey to grey fine-grained dolomitic limestone and pale grey limestone. Small thrombolitic mounds are present and cross-bedding is common. Individual beds vary in thickness from 5 cm to over 7 m. Throughout the formation beds of brown to black cherts and chert-like silicified dolostones occur. The upper boundary is the Devonian unconformity.

Silicified macrofossils are present. The fauna primarily consists of gastropods, cephalopods and occasional brachiopods, sponges and trilobites.

Conodonts recorded from the upper part of the formation are Middle Ordovician in age (Smith & Bjerreskov 1994), and the Lower to Middle Ordovician boundary is probably within the lower part of the Narwhale Sound Formation (Fig. 2; Stouge 1978; Smith 1991).

Albert Heim Bjerge

The Albert Heim Bjerge are bounded by Wordie Gletscher to the north-east and Reservatet to the north (Fig. 1). The major E–W-trending valley of Promenadedal and the river Vibeke Elv form the southern limit of the study area (Fig. 1). The area is noted for the exposures of the Middle Ordovician Heimbjerge Formation, which is the youngest preserved pre-Caledonian unit in this part of North-East Greenland (Bütler 1940; Cowie & Adams 1957; Frykman 1979). As is the case on Ella Ø, Devonian clastic sediments unconformably overlie the Ordovician rocks.

Investigations in the Albert Heim Bjerge area were focused on the 'Black Limestones' of the Cape Weber Formation and the type area of the Heimbjerge Formation (Fig. 1, section 6; Cowie & Adams 1957).

Cape Weber Formation

Cowie & Adams (1957) subdivided the Cape Weber Formation in the Albert Heim Bjerge into 'Lower Limestones', 'Black Limestones', 'Upper Limestones' and 'Dolomites and Dolomitic Limestones'. The 'Black Limestones' facies has so far only been distinguished in the Albert Heim Bjerge area (Cowie & Adams 1957), where it is 80–100 m thick and consists of black, bituminous wackestone to grainstone with shaly partings, and with chert in the upper part. Fossils are common and trilobites, including a species of the cosmopolitic genus *Carolinites*, have been reported (Cowie & Adams 1957). In 2001 macrofossils were collected from the 'Black Limestones', and samples were collected throughout the unit for conodont studies.

The 'Black Limestones' represent a deep-water marine incursion on the outer margins of the platform of North-East Greenland. On Ella Ø the coeval interval may be either the dark limestones and cherts of the upper part of Unit C, or the dark bituminous limestones of Unit D.

Heimbjerge Formation

The basal 10–15 m of the Heimbjerge Formation are dominated by brown and dark red laminated lime mudstones with birds-eye structures, stromatolites and bioturbated limestones. Above follows *c.* 50 m of laminated, grey brown lime mudstone with intraclast conglomerates overlain by platy carbonate mudstones with thin layers of calcite. A further 10 m are represented by a heterogeneous succession of massive and platy limestones, in places bioturbated, and marked by the development of small stromatoporoid mounds. Thick beds of light grey, bioturbated clean wacke- to grainstones with discontinuous horizons of chert nodules occur throughout the overlying 80 m of section. The highest exposed 50 m comprise a platy limestone facies dominated by the development of stromatoporoid bioherms. The preserved succession of the Heimbjerge Formation is only 300 m at the type locality in Albert Heim Bjerge, but Frykman (1979) recorded more than 1200 m of strata belonging to the formation on C.H. Ostenfeld Nunatak about 25 km to the north (Fig. 1). The Heimbjerge Formation is Whiterockian in age (Middle Ordovician; Smith & Bjerreskov 1994).

Thermal and burial history of the Ella Ø succession

Smith (1991) briefly reported on the conodont alteration indices (CAI; Epstein *et al.* 1977) from the upper Lower to Middle Ordovician rocks of the study area. Low values (CAI 1–1.5) are characteristic for the study area, and higher values (CAI 2) are found in the C.H. Ostenfeld Nunatak succession to the north (Smith 1991). The provisional results of CAI studies on samples collected in 2000 and 2001 are reported below.

The sequential change in colour of conodont elements reflects the progressive and irreversible alteration of organic matter preserved in the conodont elements in response to temperature, usually a consequence of thickness of overburden. The CAI values 1–5 have been experimentally calibrated with temperature ranges and correlated with other indices of organic metamorphism by Epstein *et al.* (1977). Thus, CAI 1 (50–80°C) and CAI 1.5 (50–90°C) are unaltered to nearly unaltered pale-yellow to yellow conodont elements, CAI 2 (60–140°C) are yellow to light brown, whereas CAI 3 (110–200°C) comprises brown altered conodont elements.

CAI determinations from limestones of the Antiklinalbugt Formation on Ella Ø give values of CAI 3 decreasing upwards to CAI 1.5 in the Cape Weber Formation and CAI 1 in the Middle Ordovician Narwhale Sound Formation. In Albert Heim Bjerge, CAI values are about CAI 1 in the Heimbjerge Formation. The CAI values recorded from the Ordovician succession on Ella Ø suggest that increased depth of burial was the major factor for the organic metamorphism and that the subsidence in the study area occurred during the Early Palaeozoic.

A conservative estimate of the overburden responsible for the low CAI values in the Narwhale Sound Formation on Ella Ø and the Heimbjerge Formation in Albert Heim Bjerge is about 1.5 to 1.7 km. Thus, 1–1.5 km of strata of the formerly overlying carbonate sequence has been removed from the area between Albert Heim Bjerge and Ella Ø. It follows that the 1200 m thick sequence of the Heimbjerge Formation reported from C.H. Ostenfeld Nunatak by Frykman (1979) is virtually complete. Overburden estimates are based on the geothermal gradient estimates by Rasmussen & Smith (2001) in the Ordovician carbonates of the northernmost East Greenland Caledonides and the estimates of heat flow by Armstrong *et al.* (1994).

Synthesis

The summer of 2001 was devoted mainly to the Ordovician succession overlying the disconformity separating the Antiklinalbugt Formation and the Cape Weber Formation (Stouge *et al.* 2001). The hiatus corresponds to all of the Demingian Stage and the early part of the Jeffersonian Stage of the Canadian Series (Fig. 2).

Faunal evidence from the Cape Weber Formation shows that the four informal units (A–D) represent most of the Jeffersonian and the Cassinian stages of the upper Canadian Series. The Canadian–Whiterockian Series boundary is apparently conformable and can be placed within the lower part of the Narwhale Sound Formation. The Heimbjerge Formation is Whiterockian in age, and sedimentary sequences younger than Whiterockian have not been recorded from the study area.

The Ordovician strata below the Demingian disconformity have conodonts with CAI values of about 3, suggesting that organic maturity had been reached. The overlying strata of the upper Canadian – lower Whiterockian above the disconformity are organically mature to immature with CAI values 1.5 to 1.

The upper Lower Ordovician – lower Middle Ordovician Cape Weber Formation and Narwhale Sound Formation represent a cycle of sedimentation beginning with subtidal facies and concluding with peritidal facies. There is a change from deposition on a slow subsiding passive margin to a faster subsiding margin characterised by rapid accumulation of carbonates. The cycle concluded with a regression in early Whiterockian time.

The 'Black Limestones' of Albert Heim Bjerge and the coeval strata on Ella Ø possibly mark the global sea-level rise corresponding to the '*evae*' transgression (= zones H–I), which is the highest sea-level stand in the Early Ordovician (Stouge 1982; Barnes 1984; Fortey 1984; Nielsen 1992). This sea-level rise can be traced in coeval shelf and slope deposits along the margins around the Laurentian palaeocontinent (Barnes 1984), and is characterised by the appearance of marginal shelf to slope faunal elements in the shallow-water carbonates on the shelf. A second sea-level rise may also be reflected by the 'Black Limestones' that correspond to Zone J of the upper Canadian Series. In Greenland, this younger sea-level rise has been recorded from the Nunatami Formation in North-West Greenland (i.e. the 'Bifidus' shale of Poulsen 1927) and has also been recognised in western and central North Greenland (Higgins *et al.* 1991). In western Newfoundland the sea-level rise has been identified on the basis of faunal evidence (Boyce *et al.* 2000).

The Heimbjerge Formation comprises a second carbonate depositional cycle characterised by shallow-marine subtidal facies. Carbonate accumulation kept pace with sea-level change. The diverse metazoan fauna (stromatoporoids) suggests that clear water and high-energy environments prevailed.

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Authors' addresses

S.S., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* E-mail: *ss@geus.dk*

W.D.B. & I.K., *Government of Newfoundland and Labrador, Mines and Energy, Geological Survey Division, Regional Geology Section, P.O. Box 8700, St. John's, Newfoundland, Canada A1B 4J6.*

J.L.C., *Holbaek College of Education, Seminarieparken 2, Holbæk, DK-4300 Denmark.*

D.A.T.H., *Geological Museum, University of Copenhagen, Øster Voldgade 5–7, DK-1350 Copenhagen K, Denmark.*

Late Permian carbonate concretions in the marine siliciclastic sediments of the Ravnefjeld Formation, East Greenland

Jesper Kresten Nielsen and Nils-Martin Hanken

This investigation of carbonate concretions from the Late Permian Ravnefjeld Formation in East Greenland forms part of the multi-disciplinary research project *Resources of the sedimentary basins of North and East Greenland* (*TUPOLAR*; Stemmerik *et al.* 1996, 1999). The *TUPOLAR* project focuses on investigations and evaluation of potential hydrocarbon and mineral resources of the Upper Permian – Mesozoic sedimentary basins. In this context, the Upper Permian Ravnefjeld Formation occupies a pivotal position because it contains local mineralisations and has source rock potential for hydrocarbons adjacent to potential carbonate reservoir rocks of the partly time-equivalent Wegener Halvø Formation (Harpøth *et al.* 1986; Surlyk *et al.* 1986; Stemmerik *et al.* 1998; Pedersen & Stendal 2000). A better understanding of the sedimentary facies and diagenesis of the Ravnefjeld Formation is therefore crucial for an evaluation of the economic potential of East Greenland.

The original field work was carried out in 1998, when sampling was undertaken of representative carbonate concretions and surrounding beds from a limited number of well-exposed sections in the Ravnefjeld Formation. The sampled material was subsequently investigated by a combination of petrography and stable isotope chemistry to decipher the relationships between the diagenetic development of the carbonate concretions and the mineralisation in the sequence. The sequential precipitation of the cement generations was analysed in cement-filled primary voids in gastropods because these showed the most complete development of the different cement generations. The geochemistry of stable isotopes ($\delta^{13}C$, $\delta^{18}O$ and $\delta^{34}S$) was also studied (Nielsen 2001). During the petrographic work, we became aware of a hitherto unrecognised biota dominated by calcispheres. The well-developed cement generations in primary cavities in skeletal material were used to elucidate the diagenesis.

Geology and carbonate concretions

The East Greenland Basin was formed through a combination of Late Carboniferous rifting and Early Permian subsidence related to thermal contraction of the crust (Surlyk *et al.* 1986). A major transgression in the Upper Permian brought a change from continental to marginal marine deposition characterised by the formation of fluvio-marine conglomerates, hypersaline algae-laminated carbonates and evaporites. After a new regressive phase with the development of karstified palaeosurfaces (Surlyk *et al.* 1984, 1986), a eustatic sea-level rise led to the establishment of marine conditions under which the muddy sediments of the Ravnefjeld Formation were deposited in a partially restricted basin with euxinic (super-anoxic) bottom water (Fig. 1; Piasecki & Stemmerik 1991; Nielsen 2001). Contemporaneously, the open marine carbonate platforms and bryozoan buildups of the Wegener Halvø Formation were formed along the basin margins and on submarine structural highs, leading to a partially closed basin which was at least 400 km long and 80 km wide (Surlyk *et al.* 1986).

In the Kap Stosch area (Fig. 1), the Ravnefjeld Formation comprises calcareous and micaceous shales and bioturbated siltstones subdivided into two laminated (L1 and L2) and three bioturbated (B1, B2 and B3) intervals (Figs 2, 3). This subdivision is similar to that described elsewhere in the basin (Piasecki 1990; Piasecki & Stemmerik 1991). The thickness of the laminated intervals, including the intercalated bioturbated interval (B2), is remarkably uniform in the exposed parts of the basin and usually amounts to 12 to 15 m, whereas the lower and upper bioturbated intervals (B1 and B3) vary significantly in thickness due to the palaeotopography of the underlying karstified palaeosurfaces and structural elements (Piasecki & Stemmerik 1991).

Geology of Greenland Survey Bulletin 191, 126–132 (2002)

Compilation and lithostratigraphic correlation of profiles along the coastline of Kap Stosch indicate a sub-basin about 25–30 km wide in an east–west direction, connected by a seaway with the southern part of the East Greenland Basin (Piasecki 1990; Piasecki & Stemmerik 1991). Deposition of the basinal, shale-dominated Ravnefjeld Formation was confined to the sub-basin centre, enclosed by partly time-equivalent carbonate buildups of the Wegener Halvø Formation to the west along the post-Devonian main fault, the Stauning Alper fault, and at the Clavering Ø high north-east of Kap Stosch (Fig. 1; Christiansen *et al.* 1993).

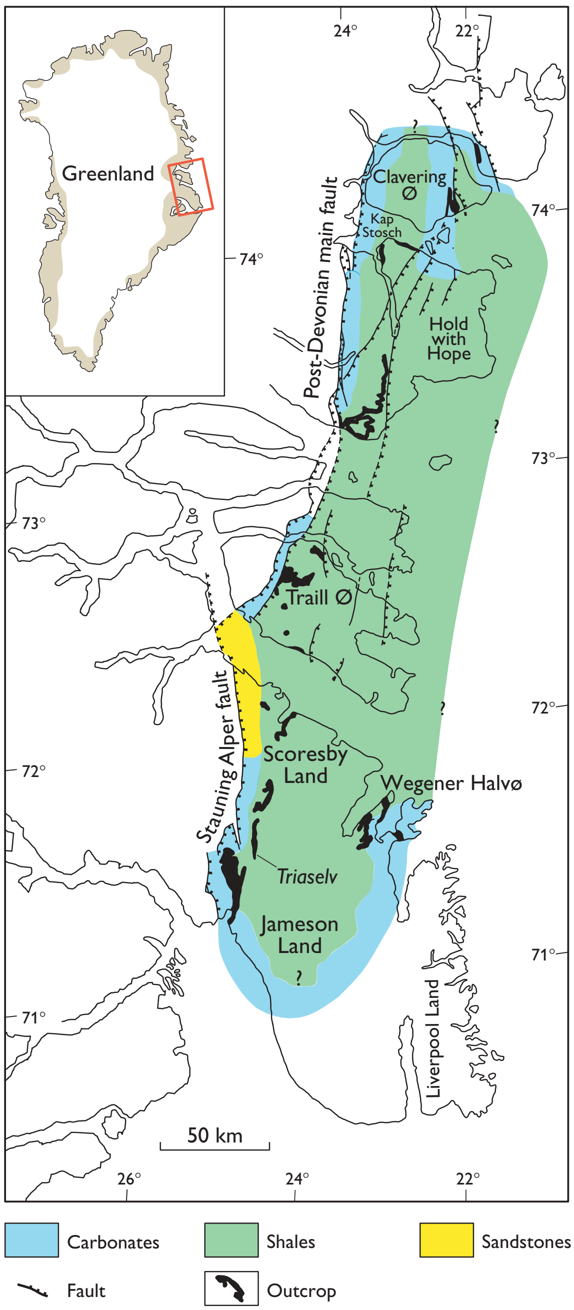


Fig. 1. Map of central East Greenland showing the distribution and extent of the Upper Permian outcrops, the shale, sandstone and carbonate facies of the East Greenland Basin and structural lineaments. Modified from Christiansen *et al.* (1993).

Carbonate concretions occur in the laminated intervals (L1 and L2) of the Ravnefjeld Formation at Kap Stosch and in the similarly developed sequence at Triaselv to the south (Fig. 1). These concretions are typically distributed in distinct horizons that are traceable throughout the outcrops in the Kap Stosch and Triaselv areas. Carbonate concretions are more frequent in the bioturbated intervals (B1 and B3) at Kap Stosch than in other parts of the basin. The concretions are

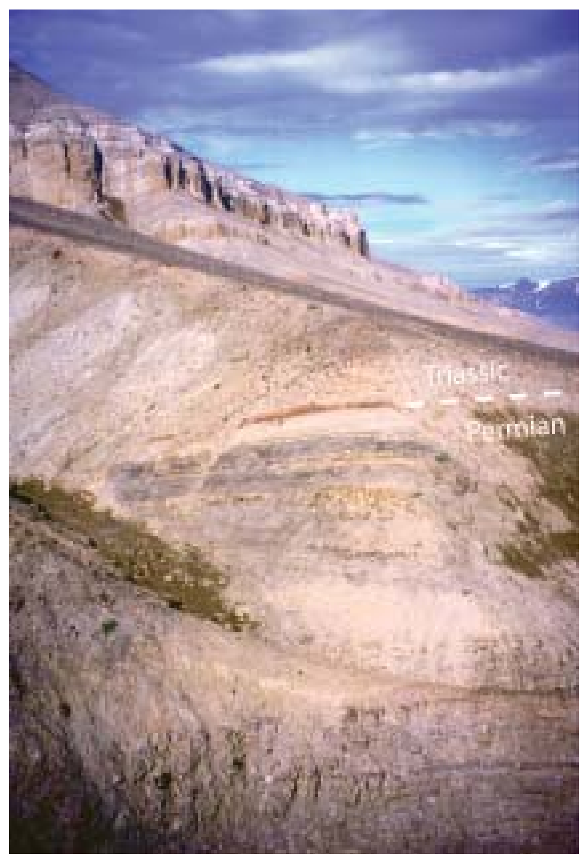


Fig. 2. The Upper Permian – Lower Triassic succession on the Kap Stosch peninsula on Hold with Hope. The Ravnefjeld Formation (*c.* 25 m shown) in the lower part of the photograph is unconformably overlain by the lowermost Triassic sediments of the Wordie Creek Formation. Dark screes are Palaeogene basalt blocks derived from about 1300 m above sea level.

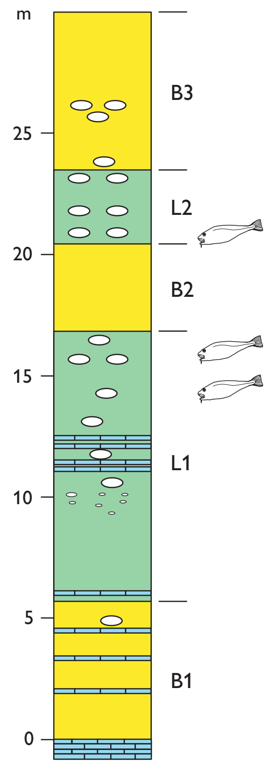
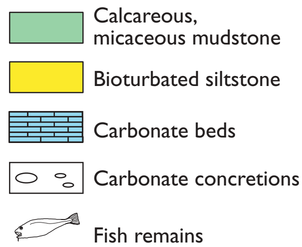


Fig. 3. Simplified sedimentological log showing the typical five-fold division of the Ravnefjeld Formation. **L1** and **L2** are laminated intervals, and **B1**, **B2** and **B3** are bioturbated intervals. The compilation is based on lithological features observed at Kap Stosch and Triaselv, and elsewhere in the region (Piasecki 1990; Piasecki & Stemmerik 1991; Nielsen 2001).



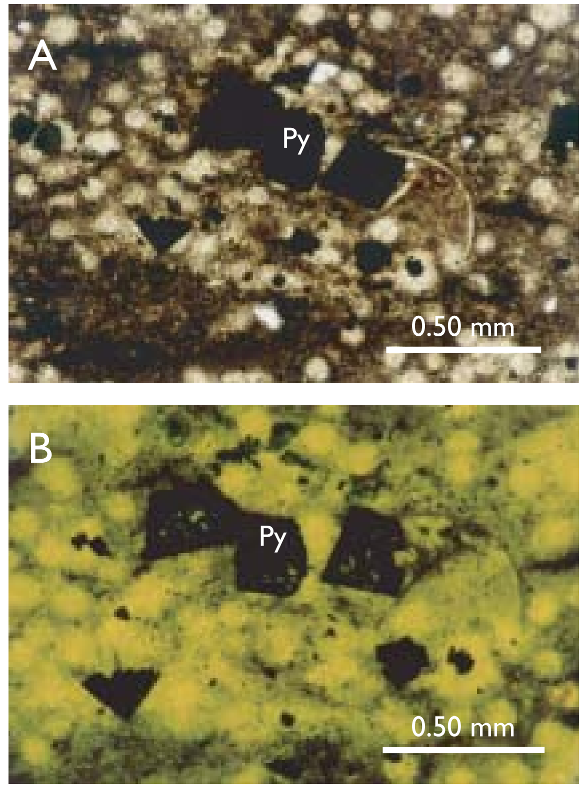


Fig. 4. Micrographs of the abundant calcispheres, partially replaced by euhedral pyrite (**Py**) as viewed in transmitted light (**A**) and ultraviolet fluorescence (**B**) (sample GGU 446352). The pyrite contains fluorescent calcite inclusions.

slightly elliptical and range from a few centimetres to more than three metres in diameter. Their long axes are parallel to the bedding, but they show no sign of parallel orientation. Although fish remains have been found both in the concretions and in the surrounding sediments since the late 1920s (e.g. Bendix-Almgreen 1993), knowledge of the nature of concretion formation was very limited prior to initiation of the present project.

The Ravnefjeld Formation comprises most of the former *Posidonia* (originally *Posidonomya*) Shale (Newell 1955; Maync 1961) considered to be of Kazanian age, which is roughly equivalent to the European Zechstein cycle 1 (Piasecki 1984; Rasmussen *et al.* 1990; Utting & Piasecki 1995); it is of latest Wuchiapingian age, based on the conodont fauna (Stemmerik *et al.* 2001).

Biological constituents of the carbonate concretions

Both pellets and trace fossils are very common in the carbonate concretions. The pellets show signs of bedding-parallel, compactional deformation, indicating loading due to overburden before cementation.

Some carbonate concretions contain a rich skeletal fauna consisting mostly of small fragments due to mechanical breakage before final deposition. No systematic investigation of the skeletal fauna has been undertaken, but some aspects that are important for the facies analysis and diagenesis of the Ravnefjeld Formation are pointed out.

Calcispheres (calcareous, hollow, spherical bodies about 75–200 microns in diameter) are very abundant in the laminated concretions from the L1 and L2 intervals (Fig. 4A, B). The origin of calcispheres has been a matter of debate, but most are believed to represent reproductive cysts of green algae belonging to the family Dasycladaceae (Wray 1977). Upper Palaeozoic calcispheres are often encountered in shallow-water deposits (especially in restricted or back-reef environments), and as such they provide a useful palaeoenvironmental indicator. This interpretation is in good agreement with Piasecki & Stemmerik (1991) and Nielsen

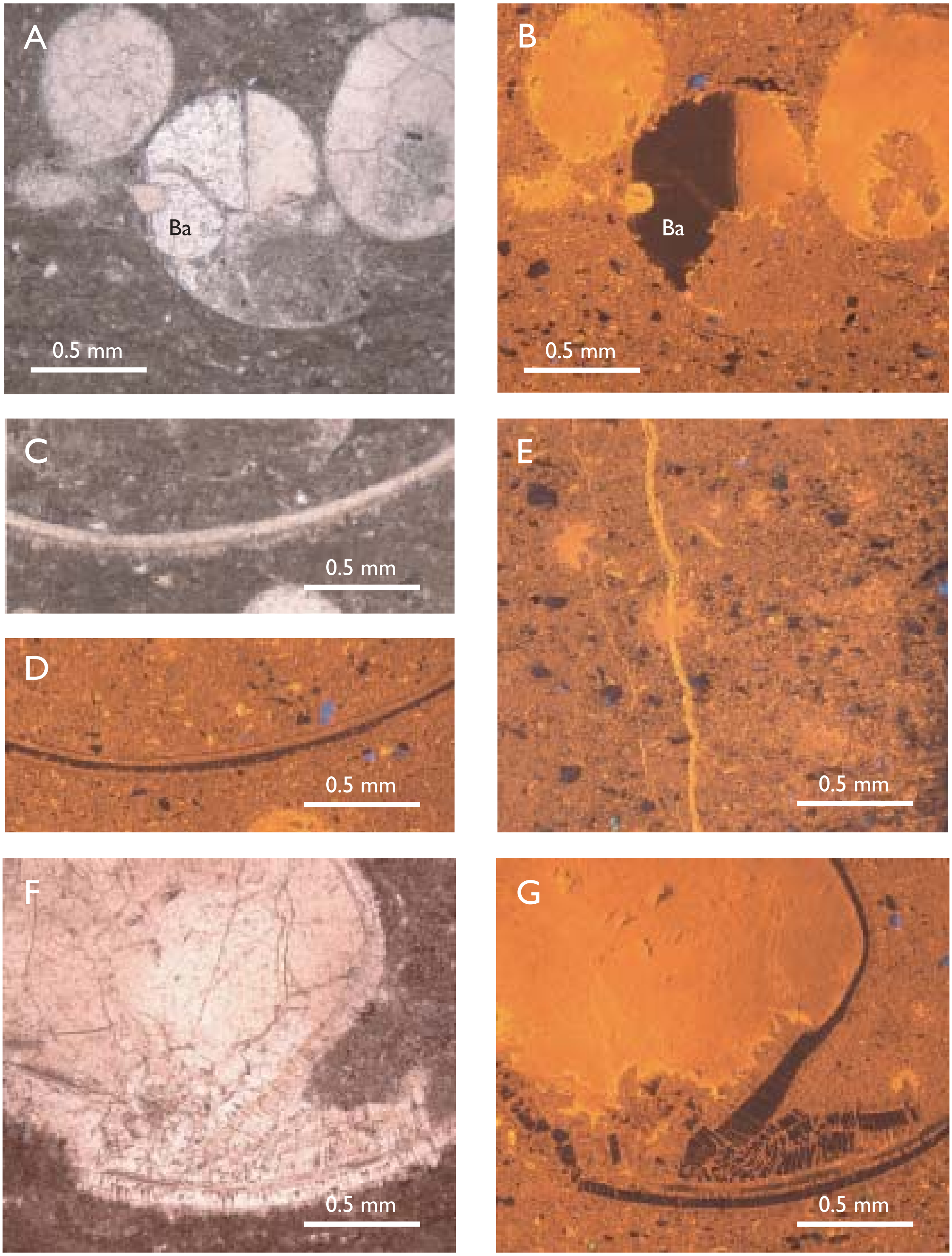


Fig. 5. Micrographs of the millimetre-sized gastropods containing authigenic calcite and baryte (**Ba**) viewed in transmitted light (**A**) and cathodoluminescence (**B**); compaction has not affected these shells. Bivalve shell in transmitted light (**C**) and cathodoluminescence view (**D**) is affected by micritisation and authigenic calcite crystals. The youngest calcite generation (**E**) is confined to veins and displays orange luminescence. Weak disintegration and displacement of the prismatic crystals of a thin-shelled fossil (**F**, **G**) followed by calcite cementation of the cavity (sample GGU 446370-2).

(2001), who pointed out the restricted nature of the basin during deposition of the sediments in the Ravnefjeld Formation.

Disarticulated bivalves of *Posidonia permica* are common in carbonate concretions from intervals L1 and L2. The bivalves have two distinct shell layers: an outer layer that has retained the original, normal prismatic microstructure, and an inner layer preserved as drusy sparite, indicating that this part of the shell was originally composed of aragonite which dissolved during early diagenesis leaving a void that was later filled with sparry calcite. The outline of the aragonitic layer has often been preserved as a dark micritic envelope (Fig. 5C, D). Such envelopes are usually produced by endolithic cyanobacteria which bore into the skeletal debris. Micritic envelopes due to endolithic cyanobacteria can be used as a depth criterion, indicating deposition within the photic zone (less than 100–200 m); this is in good agreement with the facies analysis of the Ravnefjeld Formation carried out by Christiansen *et al.* (1993).

Small gastropods occasionally occur in the carbonate concretions of the L1 and L2 intervals. Their original wall structure is preserved as drusy sparite, indicating that the shell was originally composed of aragonite that dissolved leaving a void filled with sparry calcite at a later diagenetic stage. Many specimens have a muddy geopetal fill in the lower part of the cavity, with sparry calcite filling the upper part (Fig. 5A, B).

Diagenesis of the carbonate concretions

An investigation of the cement generations in the primary cavities of gastropods has been undertaken. Since these cavities are the largest encountered in the carbonate concretions, the various cement generations are best developed here. A cathodoluminescence study of these cavities has shown a distinct pattern of zoning, representing a series of cement generations or phases of crystal growth. Each zone represents the precipitation of calcite from pore waters with different chemical compositions (Meyers 1991; Machel 2000). Four distinct calcite generations have been detected (Fig. 5B, E, G). The initial carbonate cement shows dark brown luminescence and the second generation bright yellow; both these generations are volumetrically small. The third calcite generation displays brownish luminescence and is volumetrically dominant, while the fourth and youngest calcite generation shows orange luminescence and is limited to veins cutting through all the other cement generations.

The cathodoluminescence colours in calcite cements depend upon the concentration of Mn^{2+} and/or Fe^{2+} ions (e.g. Smith & Dorobek 1993), and normally the earliest is black, precipitated from shallow oxic water, followed by yellow and brownish generations that reflect gradually more reducing conditions due to increased burial. The lack of non-luminescent carbonate cement in the concretions implies that all the carbonate cement was precipitated from reducing pore water. Prior to calcite cementation, there had also been sufficient overburden to cause incipient compaction of both pellets and thin-shelled fossils (Fig. 5F, G).

Authigenic baryte crystals are present in primary voids in some gastropods (Fig. 5A, B). Petrographic investigations show that the baryte crystals were precipitated on the yellow luminescent calcite generation, and overgrown by the brownish, indicating an early diagenetic precipitation of baryte. Baryte seems to be limited to concretions which contain a high concentration of originally aragonitic skeletal material. As shown by Turekian & Armstrong (1960) the concentration of barium in recent aragonitic gastropods and bivalves can be fairly high. If this was also the case in Upper Palaeozoic time, the early diagenetic dissolution of aragonite may have provided a local barium source for precipitation of baryte.

Both pyrite framboids and euhedral pyrite crystals are common. A combination of stable isotope analyses and a study of the size distributions of small pyrite framboids indicates that these formed within the euxinic parts of the water column while the laminated sediments were being deposited (Nielsen 2001). When they reached

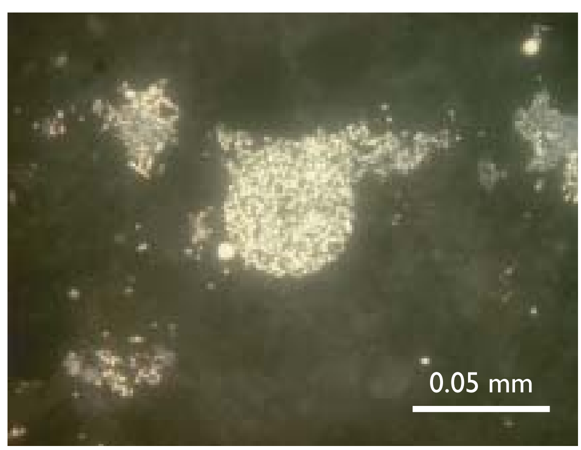


Fig. 6. Micrograph of a pyrite framboid in the bioturbated sediments (B3 interval) of the Ravnefjeld Formation (sample GGU 446358).

a maximum size of about 10 microns, they became hydrodynamically unstable and sank to the sea floor where they were incorporated in the bottom sediments (Wilkin & Barnes 1997; Cutter & Kluckholm 1999). Larger authigenic pyrite framboids are commonly found within and around burrows (Fig. 6). This association is well known from recent deposits where it results from the sharp redox transition between the burrow and the surrounding sediments arising from the decay of organic matter in the burrows during bacterial sulphate reduction (Berner & Westrich 1985). In addition to these early diagenetic pyrite framboids, later diagenetic euhedral pyrite partly replaces both the calcareous matrix and calcite cements, leaving calcareous inclusions in the euhedral pyrite (Fig. 4B; Nielsen 2001).

Chalcedonic quartz, with its characteristic bundles of thin fibres, is only known as sporadic infill in calcispheres and articulated ostracods. The silica most likely originated from the dissolution of opaline sponge spicules, which have been identified in thin sections. There is no sign of calcite cement together with chalcedonic quartz which indicates that precipitation of quartz was prior to calcite precipitation.

Rhombohedral microdolomite crystals (< 20 microns) are disseminated throughout the calcareous matrix, often associated with fecal pellets. Mesodolomite crystals (> 20 microns) occur only sparsely. As shown by Nielsen (2001), the dolomite is characterised by a depletion in ^{18}O, which indicates that the partial dolomitisation might be due to meteoric water invasion at a shallow burial depth.

Timing of the carbonate concretion formation

The investigations in the Kap Stosch area have revealed a succession of five laminated and bioturbated intervals, with several distinct horizons of carbonate concretions. The concretions studied from the bioturbated intervals B1 and B3 show well-preserved bioturbation, and this indicates that concretion formation was initiated subsequent to the infaunal activity. Compactional deformation such as deflected laminae and very thin beds at the outermost rims of the studied concretions, which are distinctive for the concretions in the L1 and L2 intervals, points to formation after some compaction. This view is also supported by the finds of slightly deformed pellets and thin-shelled fossils, which clearly indicate that some compaction of the soft, fine-grained sediment had occurred before carbonate precipitation took place.

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Authors' addresses

J.K.N., *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* Present address: *Department of Geology, University of Tromsø, Dramsveien 201, N-9037 Tromsø, Norway*. E-mail: *jesper.kresten.nielsen@ibg.uit.no*

N.-M.H., *Department of Geology, University of Tromsø, Dramsveien 201, N-9037 Tromsø, Norway*.

Qaanaaq 2001: mineral exploration reconnaissance in North-West Greenland

Bjørn Thomassen, Peter R. Dawes, Agnete Steenfelt and Johan Ditlev Krebs

Project *Qaanaaq 2001*, involving one season's field work, was set up to investigate the mineral occurrences and potential of North-West Greenland between Olrik Fjord and Kap Alexander (77°10´N – 78°10´N; Fig. 1). Organised by the Geological Survey of Denmark and Greenland (GEUS) and the Bureau of Minerals and Petroleum (BMP), Government of Greenland, the project is mainly funded by the latter and has the overall goal of attracting the interest of the mining industry to the region.

The investigated region – herein referred to as the Qaanaaq region – comprises 4300 km^2 of ice-free land centred on Qaanaaq, the administrative capital of Qaanaap (Thule) municipality. Much of the region is characterised by a 500–800 m high plateau capped by local ice caps and intersected by fjords and glaciers. High dissected terrain occurs in Northumberland Ø and in the hinterland of Prudhoe Land where nunataks are common along the margin of the Inland Ice.

The field work covered three main topics: (1) systematic drainage sampling, (2) reconnaissance mineral exploration, and (3) geological mapping. It was carried out between 22 July and 30 August by the authors assisted by two young men from Qaanaaq (Thomassen 2001). A chartered 75-foot vessel, M/S *Kissavik,* served as a base, working from 12 anchorages (Fig. 2). Two rubber dinghies enabled access to coastal localities and a helicopter was available for a 14-day period. The work was initiated in the north where the winter sea ice breaks up first, then continued in Inglefield Bredning to reach the outer islands and Olrik Fjord at the end of August. This ensured that reasonable ice conditions were encountered in all areas, apart from innermost Inglefield Bredning, north of Josephine Peary Ø, where thick calf ice rendered navigation impossible. Sixty percent of the field period was seriously hampered by bad weather, with seven days completely lost. Regional coverage was therefore not as thorough as planned.

Geological setting and map status

The Qaanaaq region is underlain by two bedrock provinces: a high-grade Archaean–Palaeoproterozoic crystalline shield overlain by the unmetamorphosed Mesoproterozoic sediments and volcanics of the intracratonic Thule Basin. The profound unconformity between these units is well preserved. The Thule Basin straddles the northern extremity of Baffin Bay, and the western outcrops are in coastal Ellesmere Island, Canada (Fig. 1). In Greenland, exposures of the Thule Basin crop out on islands and the outer coastal areas, bordered on the east by the crystalline shield.

The Qaanaaq region has not been systematically mapped at a consistent scale. The western part where the Thule Basin is exposed has been mapped at 1:100 000; the area at the head of Inglefield Bredning, composed entirely of the crystalline shield, has been depicted at 1:200 000 (Dawes 1988). The only detailed mapping undertaken was of the Smithson Bjerge (Nutman 1984). The Survey's 1:500 000 geological map sheet (Thule, sheet 5; Dawes 1991) has a northern border at 78°N; the northernmost part of the project region around Kap Alexander is featured in Dawes (1997) and Dawes *et al.* (2000).

Much of the Survey's mapping work for the Thule 1:500 000 map sheet (1971–1980) was based on shoreline investigations with only limited helicopter traverses inland. The helicopter support during *Qaanaaq 2001* was reserved for geochemical sampling and mineral reconnaissance, but enabled some inland areas to be visited for the first time leading to new geological observations and revision of some boundaries.

Geological results

Geological results given here are mainly those having significance for mineral potential. Where not otherwise stated, rock unit names are those used on the Survey's 1:500 000 geological map sheet (Dawes 1991).

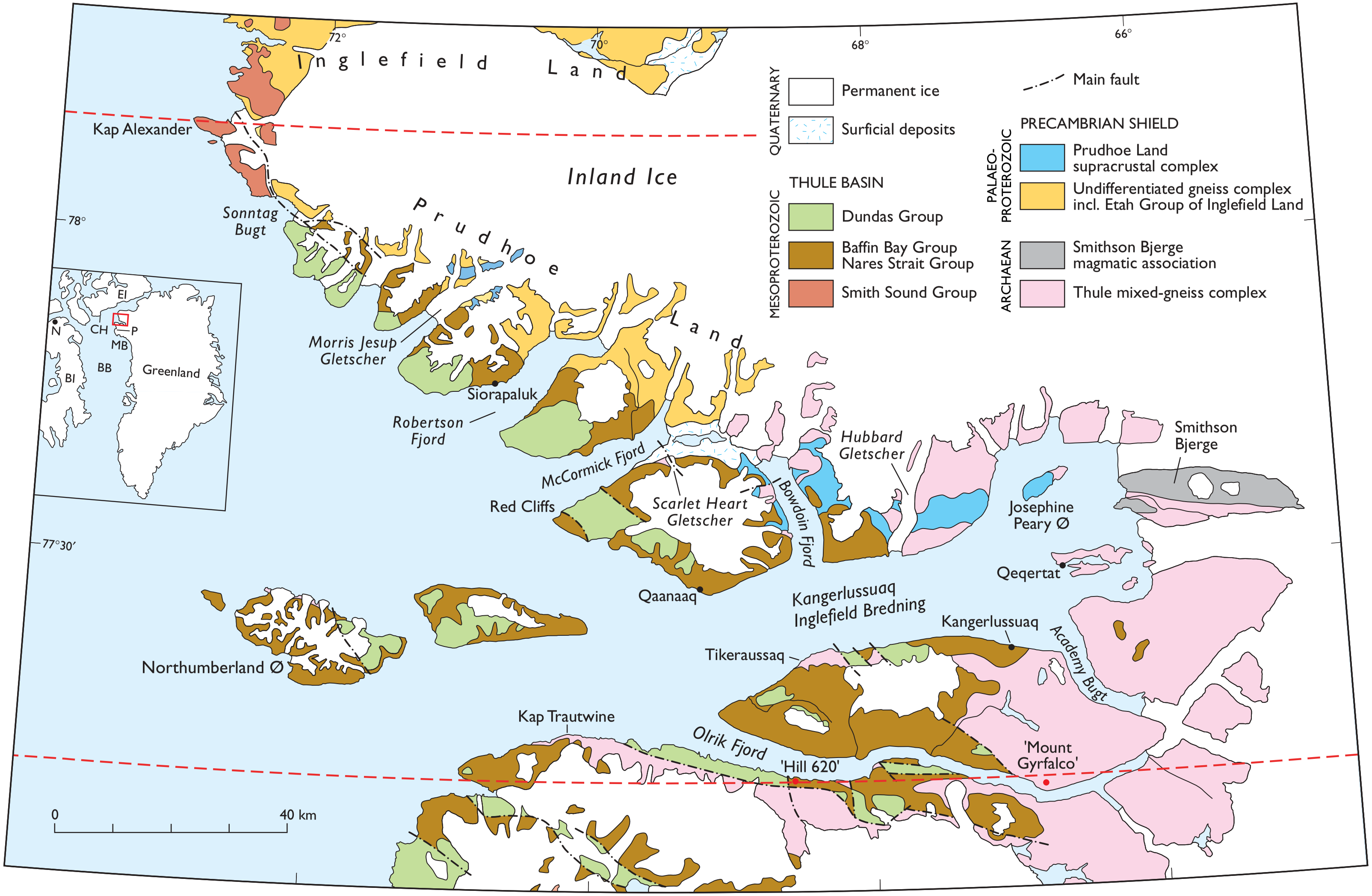

Fig. 1. Geological map of the Qaanaaq region with place names used in the text; project limits of *Qaanaaq 2001* are shown by **red dashed lines**. Basic sills, that in some areas of the Dundas Group form large outcrops, are not shown. Only faults affecting disposition of groups of the Thule Supergroup are depicted. **Black dots** are settlements; **red dots** other localities. Inset map: **BB**, Baffin Bay; **BI**, Baffin Island; **CH**, Clarence Head; **EL**, Ellesmere Island; **MB,** Melville Bugt; **N**, Nanisivik; **P**, Pituffik (Thule Air Base). **Red frame**, location of Qaanaaq region. Compiled from Dawes (1991) and Dawes *et al.* (2000) with modifications from *Qaanaaq 2001*.

Precambrian shield

Thule mixed-gneiss complex. This is an Archaean complex of highly deformed amphibolite- to granulite-facies gneisses of variable lithology and derivation, with genetically related granitic rocks. The 2001 work confirmed the intricate association of paragneisses and orthogneisses and it is clear that some intermixed packages can only be unravelled by future detailed mapping. Of note are widespread light coloured garnet-bearing quartzitic layers interleaved with gneisses. At the head of Olrik Fjord, these rock associations contain a rusty unit of banded iron-formation (BIF), e.g. north-east of 'Mount Gyrfalco' (see later under *Mineralisation*). Several amphibolite bodies were found to grade into ultramafic rocks and new occurrences of ultramafic bodies were discovered, the largest being a boudin (*c*. 500 × 150 m) within orthogneiss at the head of Academy Bugt.

Prudhoe Land supracrustal complex. These supracrustal rocks, of supposed Palaeoproterozoic age, comprise a thick succession of pelitic, semi-pelitic and quartzitic rocks with some mafic units (amphibolite and pyribolite). The supracrustal complex has conspicuous rusty weathering, and is considered to be a cover sequence to the Thule mixed-gneiss complex (Fig. 3). Both units are interleaved by large-scale isoclinal folds. New outcrops of supracrustal rocks were noted around Bowdoin Fjord and in Robertson Fjord, and units of marble, not hitherto known in the succession, were discovered at Bowdoin Fjord and Morris Jesup Gletscher. This strengthens our view that the supracrustal rocks are a correlative of the Etah Group of Inglefield land in which marble units are common.

Fig. 2. The basic logistics of *Qaanaaq 2001* with typical weather: M/S *Kissavik* and rubber dinghies with overcast, low cloud and rain. View is across Olrik Fjord in late August.

Thule Basin

The Thule Supergroup is a thick, multicoloured, mainly shallow water sedimentary succession with one main interval of volcanic rocks. Basic sills are common at several levels. Five groups are recognised (Dawes 1997), all but one of which (Narssârssuk Group) crop out in the Qaanaaq region (Fig. 1). The Smith Sound Group, present north of Sonntag Bugt, represents the northern basin margin equivalent of the Nares Strait Group and the overlying Baffin Bay Group.

Access to inland exposures in 2001 resulted in some adjustments to group/formation distribution on existing maps. One revision concerns the distribution of the Nares Strait Group with its volcanic component of hypabyssal, effusive and pyroclastic rocks and associated red beds – the Cape Combermere Formation (Dawes 1997). Breccias of the formation have proved to be mineralised. The Nares Strait Group was deemed

Fig. 3. Basement–cover relationship. Rusty-weathering pelitic and quartzitic rocks with amphibolites of the Palaeoproterozoic Prudhoe Land supracrustal complex overlying darker gneisses of the Archaean Thule mixed-gneiss complex. The pelitic schists, rich in graphite and pyrite, generate several Landsat anomalies. North side of Inglefield Bredning, west of Josephine Peary Ø, with main summit 770 m above sea level.

absent at Tikeraussaq where a postulated fault block was considered to be draped by the younger Baffin Bay Group. In 2001, a greenish basaltic unit, at least 20 m thick and in places veined and brecciated, was located within a red bed section directly overlying the crystalline shield: this succession is now referred to the Nares Strait Group. Similar basaltic rocks are also present at Bowdoin Fjord, and in 2001 were also identified farther to the east at Hubbard Gletscher. In North-West Greenland, the Cape Combermere Formation has its maximum thickness on Northumberland Ø (*c.* 200 m); it thins eastwards towards the basin margin, petering out somewhere between Hubbard Gletscher and Kangerlussuaq.

Structure

Compared to the gneisses and supracrustal rocks of the Precambrian shield, the Thule Supergroup is little disturbed; the main structures are fault blocks, grabens and large-scale flexures, as well as some local folds associated with faults. Prominent faults vary from NW–SE-trending, e.g. the fault blocks of Prudhoe Land, to ESE–WNW-trending as in the Olrik Fjord graben in which the Dundas Group is downthrown against the shield (Fig. 1). In 2001, new faults of both trends were located. Of these, a steep fault at Scarlet Heart Gletscher (Fig. 1) has appreciable downthrow, juxtaposing the Baffin Bay Group against gneisses of the shield.

Remote sensing study: a prospecting tool

An integral part of the *Qaanaaq 2001* project was a pre-season remote sensing study of the Qaanaaq region aimed at delineating areas of potential economic interest. This study was based on four images of Landsat 7 ETM data recorded during the season of minimum snow cover. The aim was to pin-point localities with mineralisation potential by means of mapping minerals that carry iron oxides (rust zones) and hydroxyl ions (argillic alteration).

Two different techniques were used for the processing of the data: (1) standard band ratios (Crippen 1989) and (2) feature-oriented Principal Component Analysis (PCA, also called the Crosta technique after its originator: Crosta & McMoore 1989). Anomalies were registered, where an anomaly is defined as a pixel where both processing techniques gave a digital number (DN) above 253, corresponding to 0.0008% of the data, in both the iron oxide and the alteration images. Using this criterion, 28 anomalies were registered: two in the Thule mixed-gneiss complex, eleven in the Prudhoe Land supracrustal complex, four in the Baffin Bay Group and eleven in the Dundas Group. For field use the image data were reproduced as paper copies of Crosta maps.

A rough distinction between the major lithological units was apparent in the image data with the Dundas Group showing up as iron oxide stained. Unfortunately, this meant that small erosional windows or isolated exposures of the Dundas Group were registered as anomalies that proved of little interest from a prospecting viewpoint. Previously known zones of alteration and rust colouring were all represented by anomalies in the image data and most of these were visited; e.g. the rusty supracrustal rocks north of Inglefield Bredning (Fig. 3). However, it became apparent that the statistical criteria selected had too high a cutoff value, as several exploration targets encountered during the season were visible in the image data but *not* registered as being abnormal. It transpires that a very small reduction of the selected DN cutoff value from 253 to 252 would have resulted in 306 anomalies. All areas of alteration and/or rust coloration observed in the field were also registered in the processed Landsat data.

Geochemical survey

The geochemical survey carried out in 2001 forms part of the reconnaissance-scale geochemical mapping of Greenland (Steenfelt 1993, 2001). The stream sediment sampling was undertaken by a two-man team using dinghy or helicopter. Prior to the field work preferred sample locations were marked on aerial photographs, the aim being to obtain an even distribution in first or second order streams with drainage basins not larger than 10 km^2.

At each location representative stream sediment material from 3 to 15 different sites along *c.* 50 m of the stream course was combined to a bulk sample of *c.* 500 g and placed in a paper bag. The total gamma-radiation from rock exposures or predominant boulders was measured using a scintillometer. A duplicate sample set of stream sediment material, collected at *c.* 5% of the localities, had the purpose of estimating the degree of local variation. Suitable streams were lacking in some of the chosen sampling sites, e.g. along glaciers and on nunataks with low relief. In such cases, scree fines or soil from patterned ground were sampled instead of stream sediment.

The sample bags were provisionally dried onboard the ship, and subsequently packed and shipped to Copenhagen where the sediments were dried, sieved and split. The fine fractions (< 0.1 mm) were analysed at Activation Laboratories Ltd, Canada, the 0.1 to 1 mm fractions were archived while fractions above 1 mm were discarded. Major elements were determined by X-ray fluorescence spectrometry using fused samples; trace elements were determined by a combination of instrumental neutron activation analysis (INAA) and inductively coupled plasma emission spectrometry (ICP-ES).

Results

A total of 343 stream sediment samples from 331 locations were analysed. Summary results are shown in Table 1 for 37 trace elements together with lower detection limits for the analytical methods. In cases where the same trace element has been determined by both INAA and ICP-ES the most reliable data are presented. Complete evaluation of the chemical data has yet to be undertaken, and here only some features of interest to mineral exploration are presented.

High concentrations of one or more elements in a sample may reflect mineralisation, or the presence of rock units with unusual chemistry. Figure 4 shows all sample locations together with locations with high concentrations of Au and the base metals Cu, Ni, Pb and Zn. The highest concentrations, i.e. anomalies, are defined here as those above the 98th percentile of the frequency distribution for an element.

Gold anomalies are scattered, with no clusters suggesting mineralisation of any particular stratigraphical unit or tectonic structure. However, the three anomalies occurring in the Thule Supergroup, i.e. from Northumberland Ø, the snout of Hubbard Gletscher and the south coast of Inglefield Bredning, are tentatively related to occurrences of volcanic rocks of the Nares Strait Group (Cape Combermere Formation). The remaining two anomalies are sited on shield lithologies.

The base metal anomalies are all associated with shield lithologies. Two conspicuous clusters are within the Thule mixed-gneiss complex. The combination of high Zn, Cu and Ni is usually attributable to mafic volcanic rocks (now amphibolite); the data therefore suggest that such rocks are part of the mixed-gneiss complex both east of the snout of Hubbard Gletscher (see Fig. 6) and in southern Smithson Bjerge. The two Pb-anomalies east of Hubbard Gletscher are in streams draining the Prudhoe Land supracrustal complex. These samples also have very high concentrations of Th and rare earth elements (REE). The highest values of Th and REE are over 10 times higher than the median values, and all anomalous samples are from streams within the Prudhoe Land supracrustal complex. Metasedimentary units enriched in heavy minerals such as monazite and garnet are probably the source of these anomalies.

The anomalous values of Zn and Pb are not so much higher than the median values, that the scattered

Table 1. Summary of chemical analyses of the < 0.1 mm grain size fraction of 343 stream sediment samples from the Qaanaaq region

Element	Method	l.l.d.	Maximum	Median	98th perc.
Au (ppb)	INAA	2	55	< 2	8
As	INAA	0.5	48	2	9
Ba	INAA	50	5400	690	1400
Br	INAA	0.5	197	3	72
Co	INAA	1	56	20	43
Cr	INAA	2	350	108	280
Cs	INAA	1	9	< 1	7
Hf	INAA	1	85	16	56
Rb	INAA	15	240	84	197
Sb	INAA	0.1	1	< 0.1	1
Sc	INAA	0.1	42	16	32
Ta	INAA	0.5	6	< 0.5	4
Th	INAA	0.2	240	17	113
U	INAA	0.5	18	3	14
W	INAA	1	19	< 1	4
La	INAA	0.5	661	53	343
Ce	INAA	3	1200	110	657
Nd	INAA	5	470	46	245
Sm	INAA	0.1	63	8	33
Eu	INAA	0.2	5	2	4
Tb	INAA	0.5	5	< 0.5	2
Yb	INAA	0.2	9	3	6
Lu	INAA	0.05	1	< 0.05	1
Ag	ICP-ES	0.3	3	1	3
Cd	ICP-ES	0.3	2	< 0.3	1
Cu	ICP-ES	1	151	33	115
Mn	ICP-ES	1	5099	656	1510
Mo	ICP-ES	1	15	2	7
Ni	ICP-ES	1	245	35	138
Pb	ICP-ES	1	77	19	47
Zn	ICP-ES	1	225	67	194
Be	ICP-ES	1	3.3	1.4	2.7
Bi	ICP-ES	2	3.7	< 2	2.5
Sr	ICP-ES	2	578	187	463
V	ICP-ES	2	269	109	212
Y	ICP-ES	1	69	23	47
S (%)	ICP-ES	0.01	0.80	0.03	0.21

All elements in ppm, except Au (ppb) and S (%).
Analyses by Activation Laboratories Ltd, Ontario, Canada.
ICP-ES: inductively coupled plasma emission spectrometry.
INAA: instrumental neutron activation analysis.
l.l.d.: lower limit of detection.
perc.: percentile of the frequency distribution.

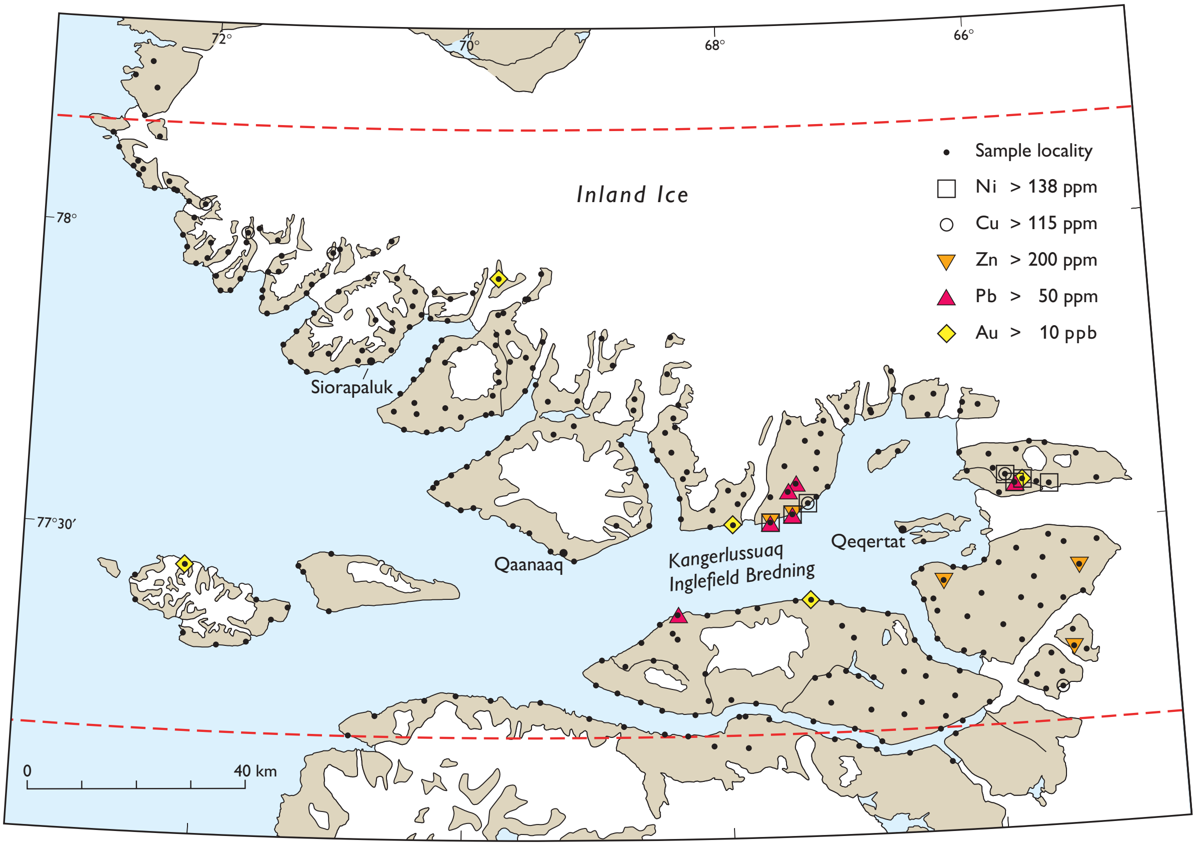

Fig. 4. Map of the Qaanaaq region showing anomalous concentrations of gold, copper, lead, zinc and nickel based on stream sediment samples. For location and place names, see Fig. 1. **Red dashed lines** demarcate the project area.

occurrences outside the clusters are considered indicative of mineralisation. Three Cu anomalies are associated with the Undifferentiated gneiss complex, but again the concentrations are not sufficiently high as to suggest significant mineralisation.

Mineral exploration

Limited mineral exploration has previously been carried out in the Qaanaaq region. In 1969 Greenarctic Consortium discovered malachite-stained sandstone at a locality known as 'Hill 620' in Olrik Fjord (Greenarctic 1971). In 1975 and 1977 the Geological Survey of Greenland (GGU) investigated selected mineral occurrences found during regional mapping (Cooke 1978), and in 1978 BIF was recorded at Smithson Bjerge by Nutman (1984). Nunaoil A/S explored the Qaanaaq region in 1994 and 1995, and reported scattered malachite in the Thule Supergroup as well as pyrite in a variety of settings (Gowen & Sheppard 1994; Gowen & Kelly 1996). Several mineralised rock samples from the Qaanaaq region collected by Greenlandic residents have been submitted to the Greenland mineral hunt programme, *Ujarassiorit* (Dunnells 1995).

During the 2001 field work a systematic visual inspection for signs of mineralisation was attempted along all the accessible coasts of the Qaanaaq region. The work was carried out partly as shoreline prospecting – observations from a rubber dinghy sailing slowly along the coast, combined with onshore investigations of promising localities – and partly as traverses of lateral and terminal moraines of active glaciers looking for mineralised blocks. This work was supplemented by limited helicopter-supported checks of inland localities. In addition to this reconnaissance work, special attention was paid to anomalies detected on Landsat images, known mineral indications, *Ujarassiorit* localities, and promising lithologies and structures. Since previous work had concentrated on the Thule Super-

Fig. 5. New iron-formation locality in the Thule mixed-gneiss complex, north-east of 'Mount Gyrfalco', Olrik Fjord. **Above**: general view eastwards of tightly folded, rusty gneisses: **arrow** marks an isoclinal fold hinge. The regional plateau surface in the distance is 500–800 m high. The cliff with the rusty scree in the left foreground is about 400 m high. **Below**: detail of banded iron-formation above with the magnet pen 12 cm long.

group, our emphasis during *Qaanaaq 2001* was on the various lithologies of the Precambrian shield.

A total of 152 mineralised rock samples were collected, mainly loose blocks from moraines, stream beds and screes. All have been analysed by Activation Laboratories Ltd, Canada, for a suite of elements including precious and base metals, and 40 of the samples have also been assayed for gold, platinum and palladium. The main results are summarised in Table 2 and commented on below.

Thule mixed-gneiss complex

Magnetite, often in the form of iron-formation, is common in paragneiss blocks wherever the Thule mixed-gneiss complex crops out. Many of these blocks are BIF consisting of mm- to cm-scale interbedded magnetite, silicates and quartz rocks, while others are near massive magnetite-silicate rocks without any obvious macrostructure. A new occurrence was found north-east of 'Mount Gyrfalco' (Fig. 5), associated with a rust zone registered as a Landsat anomaly, and consisting of a *c*. 20 m thick unit with a strike length of approximately 500 m. It comprises cm-scale interbedded magnetite, quartz, pyroxene and garnet with minor iron sulphides. Chip samples over 6.5 m returned 30.5% Fe, 2.1% Mn, 0.8% S and 8 ppb Au.

Ferruginous quartzite akin to silicate facies BIF occurs on Smithson Bjerge (Nutman 1984). Blocks of comparable quartz-garnet(-pyroxene) rocks with disseminated pyrrhotite, magnetite and traces of chalcopyrite were encountered at several localities in the eastern part of

Table 2. Summary of selected elements for mineralised rock samples from the Qaanaaq region

Geological unit	Samples	Au ppb	Cu ppm	Pb ppm	Zn ppm	Ni ppm	Ti%	Fe%	S%
Quartz veins and basic dykes	6	< 2–5	11–1081	< 3–13	3–104	4–63	0.02–3.06	1.2–10.5	0.03–3.40
Dundas Group	10	< 2–5	12–426	< 3–157	3–20986	3–48	0.02–0.49	2.0–9.4	0.07–4.46
		< 2	57	12	76	26	0.13	5.5	1.82
Baffin Bay Group	10	< 2–7	7–15247	< 3–15	4–47	1–46	0.01–0.39	0.2–3.0	0.03–2.20
		< 2	251	10	6	5	0.05	1.1	0.15
Nares Strait Group	6	< 2	30–10167	< 3–12	22–60	44–119	0.22–0.46	4.3–10.6	0.01–0.18
		< 2	920	5	33	65	0.38	4.6	0.01
Prudhoe Land supracrustal complex	14	< 2–11	8–886	< 3–135	< 1–637	< 1–581	< 0.01–3.12	0.4–21.7	0.04–18.21
		< 2	40	13	31	26	0.09	6.3	3.17
Undifferentiated gneiss complex	25	< 2–76	15–1901	< 3–171	37–1769	7–3582	0.06–1.82	1.8–15.5	0.12–6.05
		< 2	354	11	98	90	0.43	8.8	1.43
Thule mixed-gneiss complex	81	< 2–83	8–1748	< 3–45	22–793	4–3282	0.01–1.72	1.8–35.6	0.01–10.15
		< 2	123	< 3	93	50	0.24	14.8	1.11

Numbers are ranges and medians.
Analyses by Activation Laboratories Ltd, Ontario, Canada.
Analytical methods: Inductively coupled plasma emission spectrometry: Cu, Pb, Zn, Ni, Ti, S.
Instrumental neutron activation analysis: Au, Fe.

the region, but returned only slightly enhanced gold and copper values (max. 83 ppb Au and 931 ppm Cu).

Faint malachite staining, caused by oxidation of minor disseminated pyrite and chalcopyrite, was observed over a distance of 3–4 km in steep coastal cliffs of banded gneisses east of the snout of Hubbard Gletscher; this is also marked by a multi-element anomaly in the stream sediment samples (Fig. 6). Rock samples were collected at one locality, but these returned no significant metal values. Faint malachite coatings caused by minor disseminated pyrite and chalcopyrite were also observed on amphibolitic and ultramafic lenses and pods in the gneisses; samples returned up to 31 ppb Au, 8 ppb Pt, 19 ppb Pd, 1748 ppm Cu and 1298 ppm Ni.

Undifferentiated gneiss complex

A number of moraine blocks derived from this unit (see Fig. 1) contain disseminated iron sulphides, graphite and traces of chalcopyrite. Some samples are slightly enriched in gold and base metals (Table 2).

Prudhoe Land supracrustal complex

This unit is characterised by conspicuous red and yellow rust zones in sulphidic semi-pelitic schist (Gowen & Sheppard 1994), and these correspond to concentrations of Landsat anomalies (Fig. 3). Checks east of Bowdoin Fjord revealed units of highly graphitic and pyritic schist several tens of metres thick with intense argillic alteration; remobilisation of pyrite into veinlets in quartz-rich pinch-and-swell layers is interpreted as due to a hydrothermal overprint. Analyses of chip and grab samples show no significant concentrations of economic metals (Table 2).

Nares Strait Group

Blocks of malachite-stained volcanic breccia on Northumberland Ø were reported by Gowen & Sheppard (1994), and almost certainly derive from the Cape Combermere Formation. This mineralisation was found to consist of specks of malachite-covellite-chalcocite and hematite in moraine boulders collected below the Kiatak fault, a major NW–SE-trending dislocation (Fig. 1) juxtaposing the Dundas and Nares Strait

Fig. 6. Mixed orthogneisses and paragneisses, east of the snout of Hubbard Gletscher. The pale units are garnet-rich quartzites and granitic sheets. Sporadic malachite staining occurs for 3–4 km along these *c*. 600 m high cliffs and the coast constitutes a multi-element geochemical anomaly.

Groups (Dawes 1997). Samples returned up to 1.0% Cu, 11 ppm Ag and 0.9% Ba. Malachite staining has also been reported from the basal clastics of the Nares Strait Group on Northumberland Ø (Jackson 1986) as well as in the Cape Combermere Formation at Clarence Head, Ellesmere Island (Frisch & Christie 1982).

Baffin Bay Group

Faint malachite staining on pale sandstones was observed at several localities in the Qaanaaq Formation of the Baffin Bay Group. This is caused by oxidation of flecks and disseminations of minor pyrite and chalcopyrite. The highest copper concentrations were encountered at Red Cliffs and 'Hill 620'. At Red Cliffs dm-thick layers of interbedded pale sandstone and black shales occur in a small outcrop. In addition to faint malachite staining, interstitial chalcopyrite and minor pyrite were found in a composite sample which returned 1.5% Cu and 0.8% Ba. 'Hill 620' comprises an isolated, 100 × 100 m showing adjacent to an E–W-striking fault and covered by cm–dm-sized blocks of malachite-sprinkled white sandstone. The only primary copper mineral seen under the microscope is chalcopyrite as few µ sized disseminated grains. A composite sample returned 0.4% Cu and 5 ppm Ag.

Dundas Group

The Dundas Group on Northumberland Ø shows various signs of mineralisation. As noted by Dawes (1997), stratiform pyrite is common in sandy shales, but no signs of base metal concentrations were found associated with this mineralisation in 2001. In a sequence of interbedded shale and stromatolitic limestone, minor sphalerite was observed at the base of a limestone unit (Fig. 7). A composite sample returned 2.1% Zn and 0.01% Pb. Also worthy of note is the observation by Marcos Zentilli (personal communication 2002) in the same area of minor galena-barite mineralisation at a basic sill – shale contact.

Fig. 7. Interbedded dark shales and stromatolitic carbonate beds, Dundas Group, north-eastern Northumberland Ø. The base of the carbonate bed (at the notebook) contains zinc mineralisation.

Structures

The pyrite mineralisation along the syn- to post-depositional southern boundary fault of the Olrik Fjord graben noted by Gowen & Sheppard (1994) was checked at one locality, but no gold or base metals occur in the samples collected.

Concluding remarks

Observations during *Qaanaaq 2001* of magnetite-rich rocks in blocks and outcrops in the Thule mixed-gneiss complex may be interpreted as the northward extension of the Archaean magnetite province that stretches for 350 km along the coast of Melville Bugt and into the Pituffik (Thule Air Base) area (Dawes 1976, 1991; Dawes & Frisch 1981). This Greenland iron province is a prime candidate for correlation with the Algoma-type iron deposits of the Mary River Group of northern Baffin Island (Jackson 2000). In addition to iron, BIF provinces have a potential for gold, so much so that in many regions of the world BIF is used as an exploration guide for gold (Kerswill 1996).

The banded gneisses east of the snout of Hubbard Gletscher with their malachite staining and multi-element geochemical anomaly have a base metal potential. These gneisses, as well as those in the anomalous area of southern Smithson Bjerge, warrant further attention.

No convincing signs of economic mineral concentrations were found in the hydrothermally overprinted pyrite-rich graphitic schists of the Prudhoe Land supracrustal complex, but this unit needs closer scrutiny to verify whether it has gold and base metal potential. The stream sediment geochemistry suggests the presence of metasedimentary units with concentrations of REE-rich minerals.

An interesting result of the Landsat study is the presence of rust zones in the Prudhoe Land supracrustal complex and their paucity in other shield lithologies. In Inglefield Land to the north, rust zones caused by iron sulphides and graphite are concentrated in supracrustal rocks of the Etah Group and derived paragneisses (Dawes *et al.* 2000; Thomassen *et al.* 2000). This supports our view that the Prudhoe Land supracrustal complex is a correlative of the Etah Group.

The copper mineralisation in the Cape Combermere Formation of the Nares Strait Group resembles a 'volcanic redbed copper' deposit type (Kirkham 1996), possibly associated with the NW–SE-trending Kiatak fault crossing Northumberland Ø. The geochemical results for this volcanic formation also indicate a gold potential, and the formation and the faults dissecting it warrant further exploration. The disseminated copper mineralisation in sandstones of the Qaanaaq Formation of the Baffin Bay Group is probably of diagenetic origin, perhaps controlled by local faults. It constitutes a low-priority exploration target.

The carbonates of the Dundas Group with their zinc mineralisation, albeit of modest size, show a potential for carbonate-hosted lead-zinc deposits, and in this respect it is worth noting that extensive outcrops of the group occur south of the Qaanaaq region. Also of relevance is the fact that commercial lead-zinc concentrations exist in carbonate rocks of comparable age at Nanisivik in the coeval Borden Basin of Baffin Island, Canada (Olson 1984).

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Authors' addresses

B.T., P.R.D. & A.S., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* E-mail: *bth@geus.dk*

J.D.K., *Vejdammen 68, DK-2840 Holte, Denmark.*

Lake-catchment interactions with climate in the low Arctic of southern West Greenland

N. John Anderson, Sherilyn C. Fritz, Christopher E. Gibson, Bent Hasholt and Melanie J. Leng

Arctic hydrology plays a central role in the earth's heat balance and ocean circulation (Vörösmarty *et al.* 2001). Future changes associated with human influence on the climate system are also predicted to cause major changes in the energy and hydrologic mass balance of Arctic catchments. Climate change will likely affect permafrost and snowmelt, which dominate Arctic hydrology and control the chemistry of surface runoff (and hence streams and lakes) as water percolates through the active layer. However, the controls and dynamic impact of snowmelt are poorly understood, because this critical timeframe is often missed by sampling programmes. In the Søndre Strømfjord area only the broadest aspects of hydrologic variability have so far been documented (Hasholt & Søgaard 1976).

Lakes respond to climatic forcing at a variety of timescales. For example, at relatively high frequencies (days), thermal stratification can be weakened or broken down by increased wind speeds associated with the passage of frontal systems. Seasonally, lake temperatures reflect annual changes in radiative heating and ambient air temperatures (Hostetler 1995). Year to year variability in climate can reduce the ice-free period (Magnuson *et al.* 2000; Doran *et al.* 2002). Over the longer term, (i.e. Holocene, hundreds to thousands of years) changes in the hydrological mass balance of

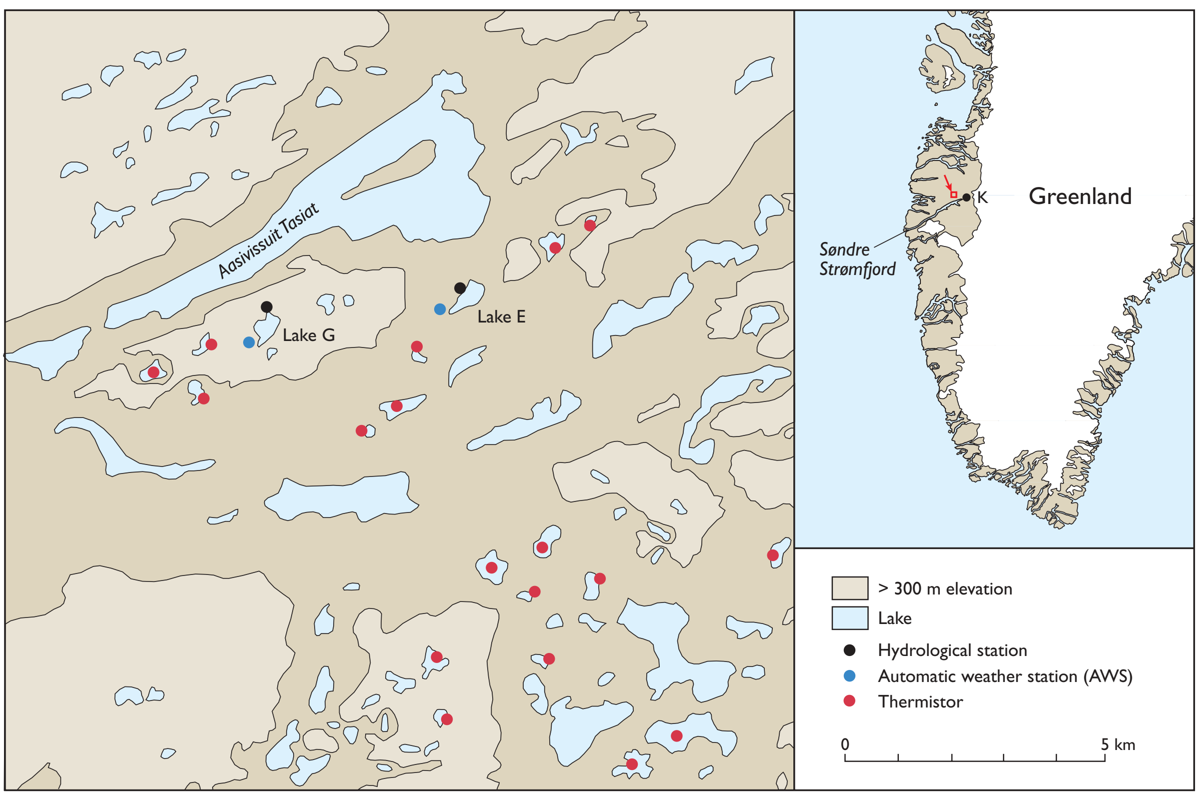

Fig. 1. Location map showing study area with hydrological monitoring stations, automatic weather stations and lakes with thermistor chains. **K**: Kangerlussuaq.

Geology of Greenland Survey Bulletin 191, 144–149 (2002)

lakes reflect hemispheric changes in climate systems and regional precipitation patterns (Overpeck *et al.* 1997). Some of these processes can be recorded in lake sediments, but it is clear that a better understanding of contemporary processes is crucial for interpreting sediment records unambiguously in terms of climate change.

The area of southern West Greenland between 66°N and 68°N contains approximately 20 000 lakes. There is a strong climatic gradient between the Inland Ice margin and the coast. The zone immediately adjacent to the ice sheet is continental with low precipitation (< 170 mm) and a mean annual temperature of –6°C. The coastal zone has a reduced annual temperature range and considerably greater annual precipitation; the summers are cooler, fog is common, and snow packs remain late into July. In contrast, closer to the ice sheet, summers are warmer and drier. Not surprisingly, the limnology of lakes in this area reflects this strong gradient. Lakes at the coast tend to be dilute and oligotrophic, whereas closer to the head of Søndre Strømfjord (Fig. 1), where evaporation exceeds precipitation on an annual basis, many of the closed basin lakes have become 'saline' due to long-term evaporation. Catchments close to the head of the fjord are characterised by minimal surface runoff during the summer – most runoff is via the active layer and occurs during the spring thaw. There are often large areas of bare rock, as well as aeolian deposits (often on the drier, south-facing slopes), and the more luxuriant vegetation is associated with damper hollows and lake outflows (Fig. 2).

Initially, our work in southern West Greenland had the aim of using the oligosaline lakes as archives of past changes in effective precipitation. Work to date has primarily been concerned with sediment core studies and long-term climate change (Anderson & Bennike 1997; Anderson *et al.* 2000). More recently, however, field activity has concentrated on two main aspects of the interaction of lakes with local and regional climatic variability: namely, timing of icemelt and patterns of thermal stratification (Anderson & Brodersen 2001). However, a more complete understanding of the hydrological links between lakes, local climate as well as their catchments is still lacking, and the rationale for the present project was therefore to combine these varying interactions in a more holistic manner.

Aims of the present project

In an attempt to integrate some of the contrasting but complementary aspects of lake-climate-catchment interactions in West Greenland, it was decided to focus specifically on a limited number of lakes and their catchment hydrology. Two neighbouring lakes were chosen, one with an outflow and one without, but both experiencing a similar regional climate and having similar geology and vegetation. The aim is an integrated study that combines an energy and hydrological mass balance of two contrasting lake catchments with measurements of contemporary and long-term sedimentation in the

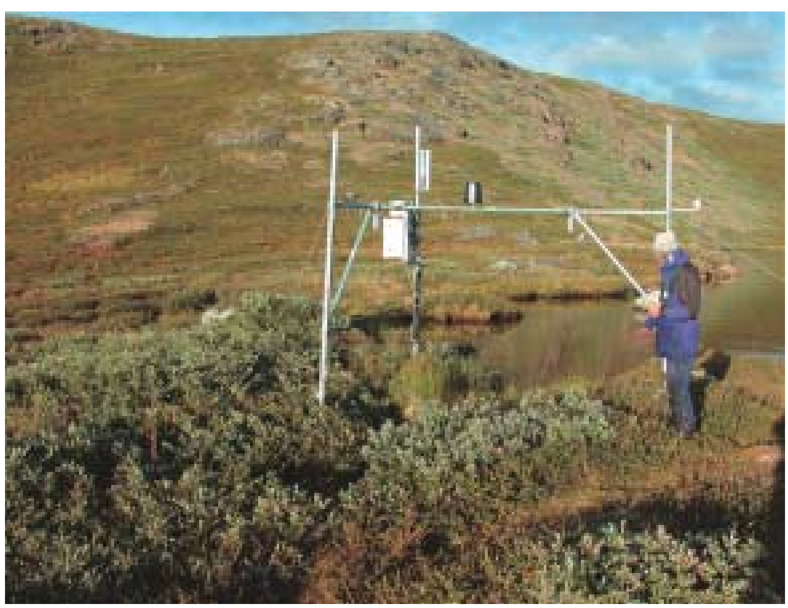

Fig. 2. The hydrological station at the outflow from Lake G in August. The more extensive vegetation growth is apparent despite there being no flow from the lake.

lakes. As in earlier reports (e.g. Anderson & Brodersen 2001), we here follow the convention of referring to the fjord as Søndre Strømfjord and the airport at the head of the fjord as Kangerlussuaq (Fig. 1).

Study sites

Field activity during 2001 was concentrated on two lakes – E and G (Fig. 1) that were identified as possible study sites during field work in May 2000 (Bindler *et al.* 2001). The lakes have contrasting water chemistry and are reasonably representative of the type of lakes that occur close to the head of Søndre Strømfjord (Anderson *et al.* 2001). Lake E is a closed-basin lake (mean conductivity is 3000 μS cm^{-1}) and is surrounded by extensive fossil shorelines (Fig. 3). In contrast, Lake G has an outflow (and consequently lower conductivity, 220 μS cm^{-1}) that drains the lake on the north side, flowing via two small ponds and a wetland area (Fig. 4) into Aasivissuit Tasiat (see Fig. 1).

Field work in 2001

Field work was conducted during three periods: late April to early May, June and August. The initial field work undertaken in late April – early May used the ice cover

Fig. 3. Looking down on Lake E. The fossil shoreline development on the far (north-eastern) shore is clear. The upper limit of the shoreline is approximately 7 m above present lake level (**arrowed**). Width of the lake is *c.* 500 m.

Fig. 4. The outflow from lake G, showing the two ponds and associated wetland areas. The hydrological station, which is just visible (**arrowed**), provides scale. The lake in the centre of the view is approximately 100 m across.

on the lakes as a platform for retrieving sediment cores ('Russian' and freeze cores) from both lakes (see Anderson *et al.* 2000 for a description of field methods). At the same time, sediment traps and strings of temperature thermistors were also deployed (Anderson & Brodersen 2001). Both lakes have laminated sediments, although the quality of laminations at Lake E deteriorates with sediment depth. Lake G, however, is characterised by fine, calcite laminated sediments throughout its length.

The Technicap sediment traps (~1 m high and approximately 25 kg in weight; Fig. 5A) were dropped through the ice, with the major buoyancy floats at a depth of 3 m to avoid being caught in the ice. The traps, which are fully automatic with a motorised carousel and 12 collecting bottles (Fig. 5B), were programmed to change bottles every 18 days.

The hydrological monitoring of the lakes forms an important component of the present project. In establishing the hydrological stations prior to the start of the spring thaw, it was hoped that the changes in flow and lake level associated with this critical period could be recorded. The hydrological stations, which are based on a sturdy V-shaped frame (Fig. 2), include a variety of sensors (precipitation, pressure transducers for lake level, snow depth, soil temperature, stream flow) and a Campbell Scientific CR10X data logger. At Lake G the station was set up over the outflow. At Lake E, where there is no outflow, the station was located on the western shore, straddling the lake margin. In conjunction with the hydrological station at Lake E, a new automatic weather station (AWS) was set up at the southern end of the lake. As well as standard temperature and wind monitors, this station also included a full suite of radiation sensors, a soil heat-flux sensor and soil temperature recorders. Finally, an initial snow taxation (snow depth and density) was made for both catchments. Field activity in June included a detailed mapping of the catchments using a Trimble 4000SE base station with two roving systems (a Trimble 4000SE and a Trimble Pathfinder) differentially corrected against the base station. A Topcon GTS-6 was used for more accurate surveying of the terrain immediately surrounding the lake shorelines. This surveying was to enable the development of a digital terrain model for each catchment. Lake bathymetric surveys were also undertaken.

In an effort to determine sediment transport within the catchment, a number of simple sediment traps were set out to determine surface transport and atmospheric inputs to the lakes. The hydrological stations were checked in June, and those sensors that could not be

Fig. 5. **A**: A Technicap sediment trap on the ice at Lake E prior to deployment; 26 April 2001. **B**: A sediment trap lying on the improvised raft prior to redeployment in August 2001; the collecting bottles are clearly visible.

deployed in April were put out in the lakes. An AWS previously located halfway to the coast was upgraded and moved to the shore of Lake G. Individual temperature thermistors were put in 15 additional lakes around the two detailed study sites. These continuous measurements will provide a detailed record of the variability of icemelt (in spring 2002) and summer temperatures (for both 2001 and 2002) for a specific area, with good meteorological control provided by the two AWSs.

In August, the sediment traps were emptied, and the carousels changed and re-programmed for the next 12 months. Temperature thermistors were relocated to the central deepest part of each lake on metal wires to increase their chance of surviving the winter. On all three visits during the year, samples were taken for chemical and isotope analyses of surface water, together with water-column profiling of oxygen, temperature and conductivity.

Discussion

Global climate models predict considerable future change in the Arctic, although response will not be uniform. This variability is clear from a synthesis of long-term monitoring data, which shows that around Søndre Strømfjord temperature has declined in the period 1970–2000 (Serreze *et al.* 2000). Future predicted changes include altered mass and energy inputs, with resultant increased precipitation in some areas and decreases in others. However, our understanding of the hydrological cycle in the Arctic is characterised by a relatively sparse observational network, and the length of monitoring records is often very short and sporadic. Hence it is difficult to detect trends and identify abnormal years.

Although our contemporary monitoring programme is located in a crucial area of the Arctic, where present hydrological information is limited, by necessity it will provide only a short-term view of environmental variation. Our aim, however, is to use this contemporary hydrological and meteorological data to calibrate long-term lake response. High-resolution sediment core studies can then be used to identify decadal trends in lake water conductivity. These core records can be coupled with energy-balance models derived from modern hydrological data to estimate the past climate conditions that were required to produce the past lake level (and lake water conductivity) changes. The objective of the present project, therefore, is to integrate, as far as possible across a range of temporal scales, longer-term (10^2–10^3 years) to short-term (i.e. seasonal) processes. In a multidisciplinary approach to palaeoenvironmental reconstruction, it is also planned to couple geomorphic studies of large-scale landscape features, such as palaeoshorelines and terraces, with the finer scale record embedded in the sediment cores.

Previously, a number of lake sites with finely laminated sediments have been recorded (Anderson *et al.* 1999). Although they are not annual (i.e. varves), the palaeoenvironmental significance of the changing structure of these laminations is considerable, if the dominant processes and frequency can be determined. Some of the structure can be readily interpreted, for example calcite precipitation and deposition of purple sulphur bacteria form unambiguous laminations. It is unknown, however, whether calcite precipitation in these lakes occurs under ice (due to salinisation effects associated with salt expulsion from ice) or during the summer due to photosynthesis (increasing pH), or how often this occurs. The processes underlying the interplay of other organic/inorganic fractions are even less clear. The Technicap sediment traps were originally developed for the marine environment but are ideally suited to remote Arctic lakes where regular emptying is problematical. Aspects of our catchment studies are aimed at determining how much minerogenic matter is derived from the catchment, as many of the lakes around the head of Søndre Strømfjord lack discrete inflows. The amount of material brought in during the spring thaw is also unknown. Thus the sediment traps will allow us to couple the lake sediment record with the climatic/meteorological processes giving rise to the sediment flux, both from the catchment and within the lake.

Conclusion

Understanding future changes in the hydrology of Arctic catchments will be difficult, because of the paucity of contemporary data. Similarly, our interpretation of past changes in the hydrological mass balance of lakes and catchments, as exemplified by fossil shorelines in the Søndre Strømfjord area, can only be strengthened by understanding contemporary processes. Combined with hydrologic mass balances and an assessment of the geomorphic setting, we aim to quantify seasonal sediment input through the use of sediment cores and sediment traps. These historical scenarios and the associated palaeoclimatic inferences can then be validated by lake energy balance models (Hostetler 1995).

Acknowledgements

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Authors' addresses

N.J.A., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*. E-mail: *nja@geus.dk*

S.C.F., *Department of Geosciences, University of Nebraska, 214 Bessey Hall, Lincoln, NE 68588, USA.*

C.E.G., *Department of Agriculture and Rural Development, Agricultural and Environmental Science Division, Newforge Lane, Belfast BT9 5PX, UK.*

B.H., *Institute of Geography, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.*

M.J.L., *NERC Isotope Geoscience Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.*

Glaciological investigations on ice-sheet response in South Greenland

Christoph Mayer, Carl E. Bøggild, Steffen Podlech, Ole B. Olesen, Andreas P. Ahlstrøm and William Krabill

The reaction of the world's large ice sheets to global climate change is still in the focus of scientific debate. Recent investigations have shown pronounced thinning in the southern part of the Greenland ice sheet (Inland Ice). In order to investigate the cause of the observed thinning and to judge the sensitivity of this part of the ice sheet a combined field work, remote sensing and modelling project was designed. A glaciological transect was established in May 2001 on one of the main outlet glaciers in South Greenland (Fig. 1), and the first data are now available. In addition, the history of the glacier variations during the last 40 years has been reconstructed.

The Inland Ice in relation to sea-level and climate change

During the past few decades increasing scientific evidence has indicated that global climate is changing profoundly over a wide variety of timescales, including the possibility of fast (less than centuries) temperature fluctuations of several degrees (Johnsen *et al.* 1998; Flückiger *et al.* 1999). Accumulated evidence shows that since the onset of the industrial revolution in the middle of the 19th century human activities have significantly influenced the world's climate system (Houghton *et al.* 1996). Over roughly the same period an increase in annual mean temperatures in the northern hemisphere of about half a degree has been observed (Mann *et al.* 1998), which may or may not be attributed to human activities. The relationship between human impact and natural climate variations still remains unclear, and a better understanding of the complex climate interactions is thus highly desirable.

One of the key factors in understanding the climatic system is the interaction of the cryosphere with other components of global climate. Especially important are the high reflectivity of snow and ice for solar radiation

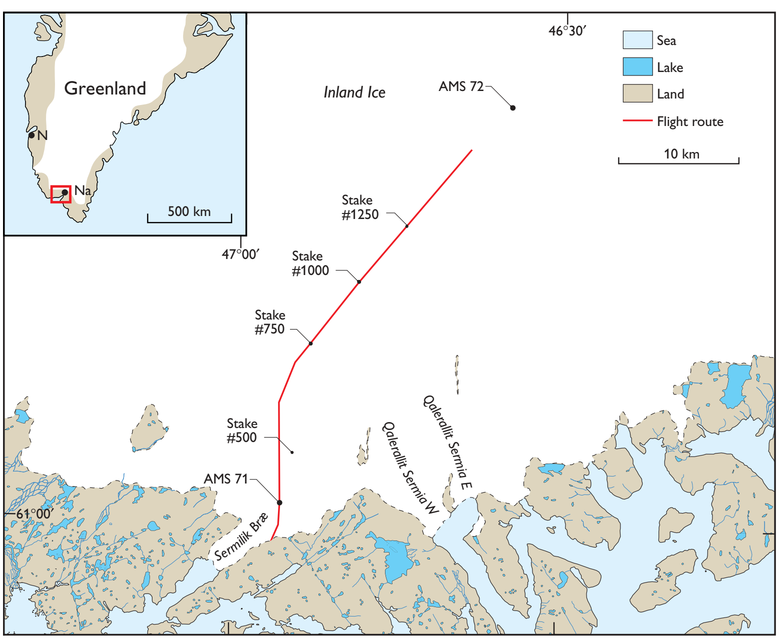

Fig. 1. Map of the investigated area and its location. The automatic mass-balance stations (**AMS**) and the mass-balance stakes are marked. The flight track of the NASA laser altimetry measurements from summer 2001 is shown in **red**. **N**: Nuuk; **Na**: Narsarsuaq. Topographic base: G/250 Vector. Copyright: Kort & Matrikelstyrelsen, 1998.

Geology of Greenland Survey Bulletin 191, 150–156 (2002)

(albedo) and the influence of meltwater runoff from the large ice sheets of Antarctica and Greenland on deep ocean water circulation (Fairbanks 1989). In addition, meltwater from glaciers and from the ice sheets have a direct influence on sea level. Fluctuations range from 120 m below the present sea level during the last glacial maximum to 6 m above in the last interglacial (130 000 to 110 000 years ago; Hvidberg 2000), where the contribution from the Greenland ice sheet may have been as much as four to five metres (Cuffey & Marshall 2000). The potential influence of the Inland Ice on future sea-level changes, as well as on climatic feedback mechanisms, therefore seems to be of considerable importance. However, present knowledge about the state of balance and especially the sensitivity of the ice sheet to short- and medium-term climate fluctuations is insufficient for a clear evaluation of its contribution to current and near future sea-level changes (Warrick *et al.* 1996).

Over the past few years great efforts have been undertaken to gain insight into the mass-balance conditions of the Inland Ice (e.g. Reeh & Starzer 1996; Van de Wal & Ekholm 1996; Ohmura *et al.* 1999; Van der Veen & Bolzan 1999; Janssens & Huybrechts 2000). One of the most comprehensive initiatives to obtain information on the state of the Greenland ice sheet is the *Program for Arctic Climate Assessment* (*PARCA*; for web address see end of paper) co-ordinated by NASA. Results from extensive field programmes, including ice-penetrating radar, laser altimetry, GPS measurements and automatic weather stations, show no substantial elevation changes in the higher parts of the ice sheet (Thomas *et al.* 2000). However, at lower altitudes areas with extensive thinning, but also minor areas of thickening, of the ice sheet seem to exist (Krabill *et al.* 1999, 2000). Specifically, strong thinning and recession are indicated for the ice margin in East Greenland, and over the south-western lobe of the Inland Ice in the study area (Fig. 1).

At present no clear answers can be given as to the state of balance of the Inland Ice and its future reaction to changing climate conditions. This holds especially for the ablation zone, where reactions may be rapid in contrast to the general millennium-scale reaction time of the ice sheet as a whole. In this area remote sensing data need to be supported and supplemented by detailed ground-based, high-resolution studies in order to detect sensitive areas and determine the governing processes.

An integrated project on marginal ice-sheet response

The study area in South Greenland is probably one of the most vulnerable areas of the Inland Ice in respect to climate induced thinning. The observed thinning rates seem to be due to a combination of variations in mass balance and the dynamic response of the ice flow to recent climatic changes (Krabill *et al.* 1999; Houghton *et al.* 2001). The main aims of the project initiated in 2001, apart from improved and continued remote sensing observations, are to improve estimates for surface mass balance from *in situ* observations and balance models, to improve modelling the dynamics of ice sheets (requiring combined studies of glaciological and satellite observations), and to establish a baseline for long-term glacier/ice-sheet observations (Houghton *et al.* 2001). The project by the glaciology group at the Geological Survey of Denmark and Greenland (GEUS) on the ice-sheet lobe in the study area is closely linked to the *PARCA* project and the ICESAT mission coordinated by NASA which is a new satellite with laser altimeter onboard. Furthermore a Ph.D. study is sponsored by the *Copenhagen Global Change Initiative* (*COGCI*; for web address see end of paper).

One of the main parts of the project is the establishment of a mass-balance transect along a representative flow line. Mass-balance measurements along this transect will allow current ablation conditions to be related to geographic position and elevation. Measurements of surface elevation, ice velocity and ice thickness are necessary for calibration of remote sensing applications and as input for ice-dynamic models.

Another main focus of the programme is to reconstruct the history of the ice-sheet margin on the basis of aerial photographs and satellite images, which extend back for nearly half a century. This time series allows detailed estimates of the mass loss, or gain, during a part of the 20th century marked by significant climatic changes. In combination with climate data for this time period, this series of images will be used as a control data set for ice-dynamic model development, which constitutes the third part of the project.

The ice-dynamic model will be specifically adapted to questions arising from the field data and general observations on thinning. This model will then be used for investigating the sensitivity and response time to changes where a new evaluation of the relationships between climate change, sea-level and ice-sheet response is anticipated.

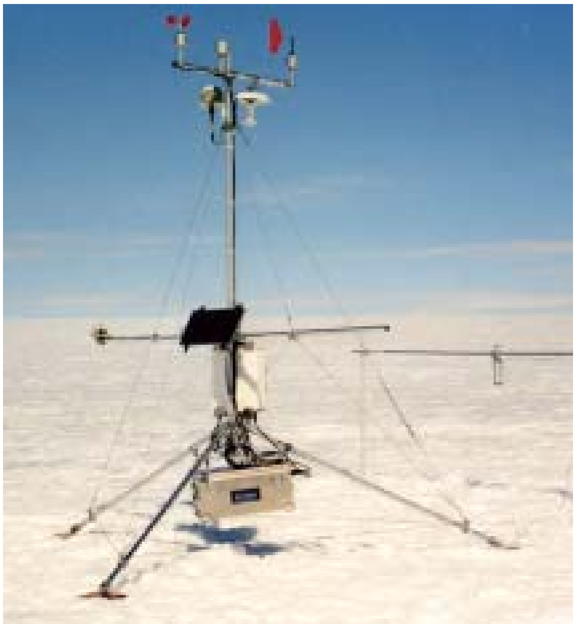

Fig. 2. The new one-mast design of the automatic mass-balance stations installed in the field in May 2001; height *c.* 2.2 m (AMS 71). The gallows with the sonic ranger for surface height measurements can be seen to the right.

Field work

In late May 2001 a glaciological transect was established on Sermilik Bræ (formerly Sermitsialik Bræ) in South Greenland at the margin of the Inland Ice. The transect extends from an altitude of 270 m a.s.l. on Sermilik Bræ (glacier code 1 AI 5001, Weidick *et al.* 1992) up to a height of 1150 m a.s.l. on the southern dome of the Inland Ice (Fig. 1). The transect consists of two automatic mass-balance stations (AMS) placed at each end of the transect and four ablation stakes placed along the flow line.

Due to the risk of loss of data in areas with high ablation rates, a new concept for the station layout has been developed to replace the former set-up of using several long stakes drilled into the ice, which often became unstable. The new AMS concept consists of one mast, supported by wires, and set on a tripod (Fig. 2). The AMS can be transported, and installed on site by two persons in about two hours. The stations measure a variety of climatic and glaciological parameters at hourly intervals. The orientation of the mast to the vertical and to magnetic north is also recorded, in order to allow for possible corrections of the parameter records.

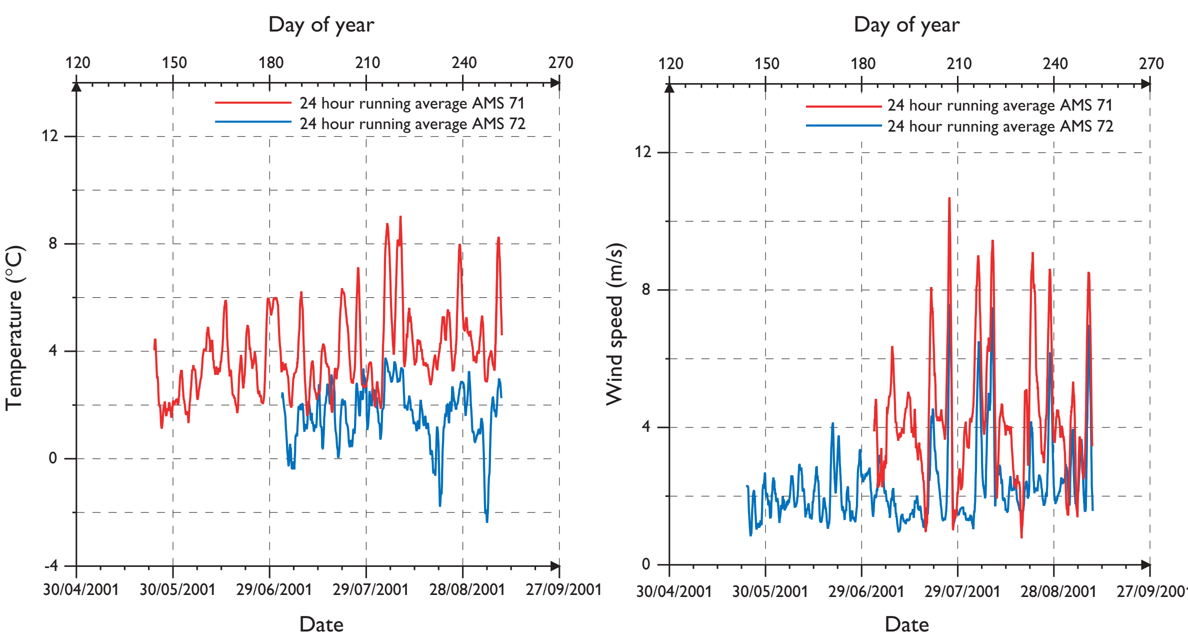

Fig. 3. Data examples from the automatic mass-balance stations for the summer season of 2001. **Red**: lower station. **Blue**: upper station. Displayed are the daily means of temperature (**left**) and wind speed (**right**) for both stations. The temperature variation ranges from –6.2 to +17.4°C for the upper and –1.1 to +12.0°C for the lower station. The maximum wind speed during the measured period was 15.8 m/s at the upper station.

Table 1. Temporal distribution of the images used for the determination of the glacier margin position

Image date	Image source				
	Aerial photography	CORONA satellites	Landsat 2 (channel 3)	Landsat 5 (channel 3)	Landsat 7 (channel 3)
05.09.1953	x (1.5 m)				
21.07.1965		x (~ 3 m)			
21.08.1967		x (~ 3 m)			
09.06.1979			x (80 m)		
09.07.1979			x (80 m)		
26.08.1980			x (80 m)		
17.07.1993				x (80 m)	
14.07.1995				x (80 m)	
04.08.2000					x (30 m)

Pixel resolution is given in brackets

In order to measure ablation automatically over several years without having to re-drill stakes at every visit, a new system was installed at the lower AMS. This consists of a ventilated stainless steel pressure transducer connected to a 20 m fibre-reinforced PVC hose filled with alcohol.

At the revisit to the site in September 2001 the new ablation system was still functioning, and the recordings from the logger are in very good agreement with data from the sonic ranger and the classically measured melting of 4.95 m in 106 days.

The positions of both AMSs and stakes were remeasured by a high-precision GPS receiver on the September visit, except for stake no. 750. The analysis of the measurements shows a velocity of the upper station of 0.4 m/day, increasing downstream to 1.4 m/day at the lower station close to the glacier front. Data records for temperature and wind speed at both stations during the summer of 2001 are shown in Fig. 3. Both parameters are generally in phase for the two stations, but temperature inversions can be found on days with very low wind speed at the lower station. The data sets for the stations will be used for further analysis of melting conditions and the distribution of melting in this area.

During the 2001 field season the NASA airborne ice radar and laser altimetry system was used for investigations in southern Greenland within the *PARCA* project. By request, one flight track was planned to cover the GEUS glaciological transect (Fig. 1). Unfortunately, the ice radar data could not provide thickness data over this track because of heavily crevassed and irregular surface conditions. However, the laser altimetry data are of very good quality, and are currently being analysed in combination with the GPS measurements and information from the satellite images.

Glacier-margin detection from satellite imagery

During the past 50 years the glacier Sermilik Bræ has undergone significant variations in its dimensions. Within

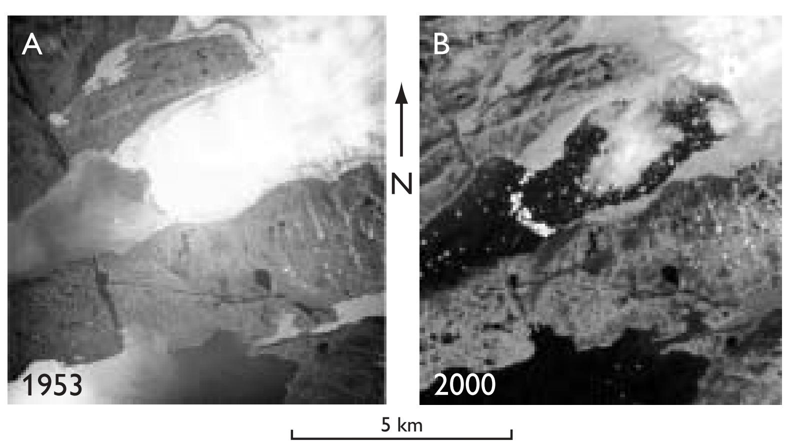

Fig. 4. Aerial views of the Sermilik Bræ region. **A**: Aerial photograph from 1953; **B**: Satellite image from Landsat 7 obtained in 2000. In the Landsat image shown in Fig. 5 Qalerallit Sermia W and Qalerallit Sermia E are also seen.

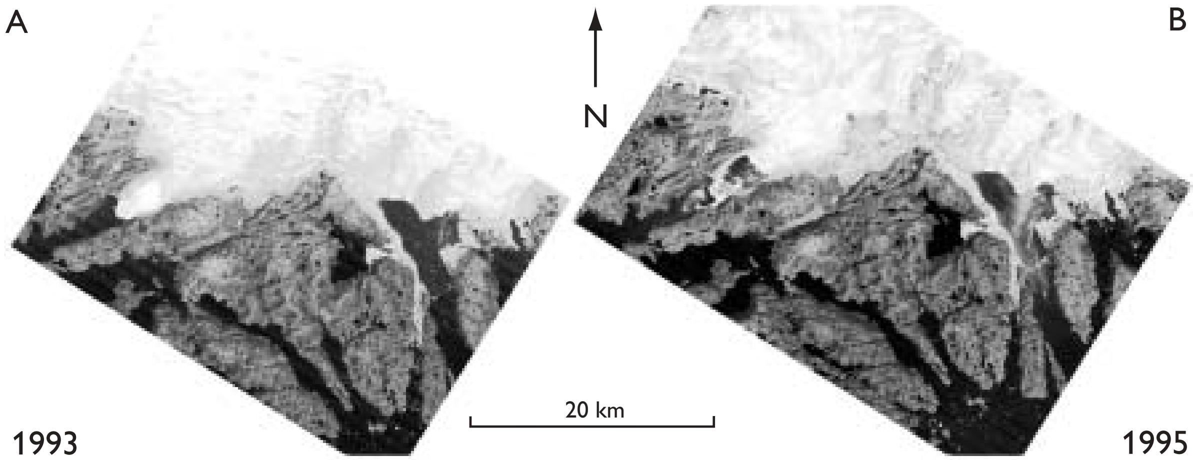

Fig. 5. Satellite images from Landsat 5 obtained in 1993 (**A**) and 1995 (**B**) showing changes of the snout of Sermilik Bræ. See also text and Table 1.

the framework of the project, investigations are focused on the retreat of Sermilik Bræ and on the two branches of Qalerallit Sermia (formerly Qaleragdlit sermia, glacier code 1 AH 02001, Weidick *et al.* 1992), the glacier to the east (Fig. 1). The retreat of these glaciers can be determined from aerial photography from 1953 and comparisons of satellite images from 1965, 1967, 1979, 1980, 1993, 1995 and 2000. The satellite images were obtained from the CORONA satellite mission and from the continuous Landsat series, including images from Landsat 2, 5 and 7. Information about the available images and the channels used is given in Table 1. As an example, the pronounced retreat of Sermilik Bræ between 1953 and 2000 is illustrated in Fig. 4.

The resolution of all images is better than 80 m, which allows a high-resolution determination of the glacier retreat over several kilometres. Identification of between 20 to 40 ground control points over the area of interest in each of the images allows correlation of all images with a master image, for which a Landsat 7 image with a pixel resolution of 30 m was used. The measurements of glacier tongue variations were determined from central flow lines on the glaciers. For Qalerallit Sermia W and Qalerallit Sermia E retreat is measured with respect to 1965 as reference year.

The earliest observations on Sermilik Bræ date from the mid-19th century, but there are insufficient records prior to 1947 to establish a continuous history of retreat or advance. Between 1947 and 1953, the glacier front of Sermilik Bræ was reported as stationary (Weidick 1959), but since 1953 our observations indicate a semi-continuous retreat. This general trend has also been observed for nearby glaciers on the series of satellite images. However, an aerial photograph from 1985 shows the glacier front of Sermilik Bræ at almost the same position as it was in 1980, followed by a retreat once again. Satellite images from 1993 show that the tongue of Sermilik Bræ was floating over several kilometres of the front at this time. The rate of retreat changed considerably between 1985 and 1993. The break up of a considerable part of the glacier tongue (Figs 4, 5) cannot yet be precisely dated. Between 1995 and 2000 retreat events sum up to about 1900 m at Sermilik Bræ (Fig. 6).

Climatic effects, such as a general global warming, cannot account for the regional retreat of the glaciers in southern Greenland. Recent studies have shown that temperatures in western Greenland and adjacent regions in the North Atlantic have experienced a slight cooling over the last half century, in contrast to the global trend (Chapman & Walsh 1993; Hansen *et al.* in press). In agreement with these findings, meteorological observations at Nuuk and Narsarsuaq have also shown a cooling trend over the last 50 years. However, relatively warmer periods have been noted between 1940 and 1950 and also during the 1980s and 1990s (Jørgensen 2001). The latter short-term temperature increases may have led to higher melt rates, particularly at the ice-sheet margin, and may be linked to the rapid disintegration of the floating glacier tongue and an associated massive ice discharge observed at Sermilik Bræ between 1993 and 1995 (Fig. 5A).

The satellite images show an extensive moraine corresponding to the position of the last major glacier advance in the late 19th century, which extends through-

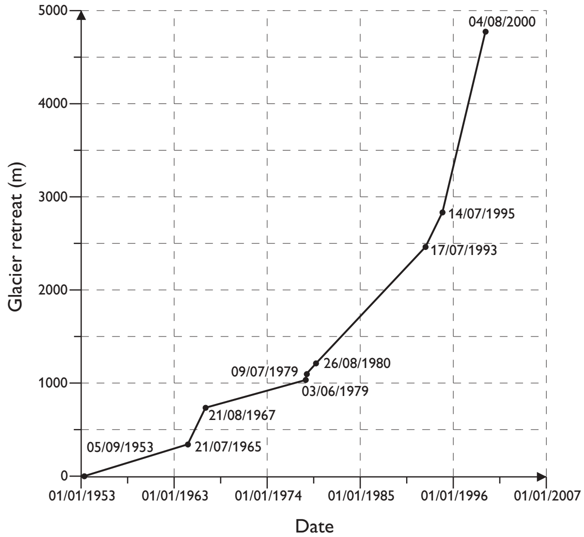

Fig. 6. Measured mean retreat of the glacier terminus of Sermilik Bræ determined from the available aerial photographs and satellite images. The total retreat accumulates to more than 4.7 km since 1953.

out the fjord. The submerged part of this moraine acts as a natural barrier, which prevents the icebergs floating out of the fjord (Figs 4B, 5B). This observation essentially corresponds to the situation described by Bloch (1893) and the outline of the glacier front on his handdrawn map.

Future perspectives

Glacier variations in southern Greenland do not seem to be related only to climatic influence on the surface mass balance. Dynamic changes in ice-sheet geometry and basal conditions connected to climatic variations on a much longer timescale appear also to be significant. With the mass-balance transect in place, and also surveyed with laser altimetry, future changes in the study area can be mapped accurately and compared with the actual climatic and surface mass-balance data, which will allow discrimination between mass-balance effects and dynamic reactions. Climatic conditions during the periods of recession of the past 40 years need to be investigated using climate data from nearby weather stations, or from climate proxy data. This compiled glacier history can then be used as a benchmark for testing of the ice-dynamic model.

Further information

PARCA project see: http://cires.colorado.edu/parca.html
ICESAT mission see: http://icesat.gsfc.nasa.gov/intro.html
COGCI school see: http://www.cogci.dk

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Authors' addresses

C.M., C.E.B, S.P, O.B.O. & A.P.A., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.*
E-mail: *cm@geus.dk*

W.K., *Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Wallops Flight Facility, Building N-159, Wallops Island, VA 23337, USA.*

Scientific publications on Greenland by the Survey, 2001

Compiled by Peter R. Dawes

Geology of Denmark and Greenland Map Series

This peer-reviewed series comprises map sheets of the national map sheet coverages of Denmark and Greenland including offshore areas planned to be issued with short explanatory notes.

Geological map of Greenland, 1:500 000, Kong Oscar Fjord, sheet 11. *Compiled by* J.C. Escher. Copenhagen: Geological Survey of Denmark and Greenland.

Geological map of Greenland, 1:100 000, Pingu 69 V.2 Nord. *Compiled by* A.K. Pedersen, L.M. Larsen, F. Ulff-Møller, G.K. Pedersen & K.S. Dueholm. Copenhagen: Geological Survey of Denmark and Greenland.

Satellite image map

This mosaic map is compiled from standard ETM (Enhanced Thematic Mapper) scenes acquired by the Landsat 7 satellite.

Iita–Savissivik, North-West Greenland, 1:300 000. *Compiled by* T. Tukiainen & B. Thomassen. Copenhagen: Geological Survey of Denmark and Greenland.

Geology of Greenland Survey Bulletin

This is a peer-reviewed series; an exception is the annual *Review of Greenland activities* which is refereed internally.

189: Review of Greenland activities 2000. *Edited by* A.K. Higgins & K. Secher, 131 pp. (17 articles). See *http://www.geus.dk/publications/review-greenland-00/gb189-uk.htm* for contents and download of articles.

190: The Ilímaussaq alkaline complex, South Greenland: status of mineralogical research with new results. *Edited by* H. Sørensen, 167 pp. (18 articles). See *http://www.geus.dk/publications/bull-gl/gree-190-uk.htm* for contents.

Danmarks og Grønlands Geologiske Undersøgelse Rapport

This open file-type series comprises *unedited* reports in limited numbers. It includes confidential reports, some of which are released when confidentiality expires. Only *unclassified* numbers dealing with Greenland geoscientific topics are listed. Manuscripts submitted for M.Sc. and Ph.D. degrees are released in this series.

2001/4: Qulleq-1 (6354/4-1): sidewall core description. Service report prepared for Statoil a.s. *By* T. Preuss, G. Dam & F. Dalhoff, 32 pp. (Released 1 April 2001.)

2001/18: Seismic data acquisition in the offshore part of the Nuussuaq Basin during summer 2000 – Cruise report. EFP-Project NuussuaqSeis 2000. Structure and hydrocarbon potential of the Nuussuaq Basin: acquisition and interpretation of high-resolution multichannel seismic data. *By* C. Marcussen, H.L. Andersen, J.A. Chalmers, P. Trinhammer, R. Rasmussen & E. Hansen, 66 pp.

2001/23: The palladium potential of the Skaergaard Intrusion, South-East Greenland. *By* T.F.D. Nielsen, 39 pp.

2001/27: A Neoproterozoic carbonate ramp and base-of-slope succession, the Andrée Land Group, Eleonore Bay Supergroup, North-East Greenland: sedimentary facies, stratigraphy and basin evolution. *By* K.S. Frederiksen, 248 pp. (Ph.D. thesis, University of Copenhagen, Denmark.)

2001/33: Qulleq-1 (6354/4-1): petrography of selected sidewall cores. Service report prepared for Statoil a.s. *By* T. Preuss & F. Dalhoff, 14 pp. (Released 1 April 2001.)

2001/42: Sen palæozoisk udvikling af den nordatlantiske rand af superkontinentet Pangæa. Dansk resumé. *By* L. Stemmerik, 7 pp.

2001/46: Geochemical atlas of Greenland – West and South Greenland. *By* A. Steenfelt, 43 pp. + CD-ROM.

2001/47: Calibration of stream sediment data from West and South Greenland. *By* A. Steenfelt, 43 pp.

2001/58: AEM Greenland 1994–1998 – summary report. *By* T.M. Rasmussen, L. Thorning, R.W. Stemp, M.S. Jørgensen & F. Schjøth, 46 pp. + CD-ROM.

2001/90: Seismic data processing of data from the NuusuaqSeis 2000 survey. EFP-Project NuussuaqSeis 2000: structure and hydrocarbon potential of the Nuussuaq Basin: acquisition and interpretation of high-resolution multi-channel sesmic data. *By* R. Rasmussen & T.D. Jensen, 30 pp.

2001/94: Sen palæozoisk palæoklima og palæogeografi i det nordatlantiske område. *By* L. Stemmerik, 11 pp.

2001/95: Sprækkeundersøgelse og beskrivelse af fjeldbeskaffenhed ved Nuuk. En forundersøgelse af to tunneler, henholdsvis til Qinngorput og Ulaajuk, udført for Nuuk Kommune af GEUS og ASIAQ. *By* P.R. Jakobsen & H.G. Karlsen, 26 pp.

2001/99: Fjeldskred ved Paatuut. Undersøgelse af fjeldskred som var årsag til flodbølge den 21. november 2000 ved sydkysten af Nuussuaq, Vestgrønland. *By* S.A.S. Pedersen, T. Dahl-Jensen, H.[F.] Jepsen, L.M. Larsen, G.K. Pedersen, T. Nielsen, A.K. Pedersen & W. Weng, 47 pp.

2001/101: Feltrapport for Qaanaaq 2001 projektet. September 2001. *By* B. Thomassen, 9 pp.

2001/102: Inventory of the literature on the Ilímaussaq alkaline complex, South Greenland. *By* J. Rose-Hansen, H. Sørensen & W.S. Watt, 42 pp. + CD-ROM.

2001/103: Stratigraphy, seismic sequences and depositional evolution of the Paleocene–Eocene succession, offshore southern West Greenland. *Edited by* J.A. Chalmers, U. Gregersen, F. Dalhoff, H. Nøhr-Hansen, J.A. Rasmusssen & E. Sheldon, 286 pp.

2001/115: Blyklippen lead-zinc mine, Mestersvig. Existing knowledge. Mineo site report. *By* P. Aastrup, M. Tamsdorf & T. Tukiainen, 39 pp.

2001/116: En vurdering af de geokemiske forhold i de grønlandske byers vandressourceoplande i relation til indflydelsen på kvaliteten af råvandet. *By* A. Steenfelt, 78 pp.

2001/117: Offshore volcanic rocks in Baffin Bay. A seismic interpretation of the structures and development of the Palaeogene offshore volcanic rocks in central West Greenland and on the Baffin Island margin eastern Canada. *By* N. Skaarup, 153 pp. (Ph.D. thesis, University of Copenhagen, Denmark.)

2001/123: The Pd + Pt dispersion in noritic and undifferentiated mafic rocks of the Archaean craton east of Maniitsoq, southern West Greenland. *By* K. Secher, 22 pp.

2001/131: Isua workshop, Berlin 17 to 20 january 2002. Harnack Haus, Berlin, Programme and abstracts. *By* P.W.U. Appel & S. Moorbath, 75 pp. (31 abstracts).

2001/132: GEUSGREEN. GimmeX database relateret til GEUS' nummersystem for geologiske prøver fra Grønland. *By* T. Tukiainen & L. Christensen, 27 pp.

2001/133: Palaeogene gold- and silver-bearing epithermal veins at Amdrup Fjord, southern East Greenland. *By* B. Thomassen & J.D. Krebs, 83 pp.

GHEXIS

Greenland **H**ydrocarbon **E**xploration **I**nformation **S**ervice is a newsletter bringing geological and regulatory information on Greenland to the international petroleum industry.

In 2001 there was a single issue (no. 19). See GHEXIS Online on *http://www.geus.dk/ghexis/* for this, back issues and other information pertaining to petroleum exploration in Greenland.

MINEX

This newsletter (Greenland **Min**eral **Ex**ploration Newsletter; formerly *Greenland MINEX News*) brings geological and regulatory information on Greenland to the international mining industry.

In 2001 there were three issues (nos 19–21). See MINEX Online on *http://www.geus.dk/minex/* for these, back issues and other information relevant to mineral exploration in Greenland.

Scientific publications in external outlets

The articles listed are international publications in English on Greenland and the surrounding seas. Articles by staff of the Danish Lithosphere Centre, Copenhagen (administratively attached to the Survey), as well as non-survey staff where the work was initiated under the Survey's auspices or expeditions, are included.

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By C.R.L. Friend, M. Brown, W.T. Perkins & A.D.M. Burwell. 155.00
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185 Greenland from Archaean to Quaternary. Descriptive text to the Geological map of Greenland, 1:2 500 000. 2000. 93 pp.
By N. Henriksen, A.K. Higgins, F. Kalsbeek & T.C.R. Pulvertaft. 225.00

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Review of Greenland activities 2001

The *Review of Greenland activities* summarises the main operations carried out in Greenland each year by the Geological Survey of Denmark and Greenland (GEUS). This volume contains 18 technical papers reflecting field projects undertaken in 2001, introduced by a directorial review. A list of the Survey's scientific publications on Greenland is also included.

The technical papers report onshore and offshore activities based on both ground and shipborne surveys and from widely spaced regions stretching from southern Greenland (60°N) to North-East and North-West Greenland (80°N). Topics include economic geology and regional mapping in the Archaean of the Disko Bugt – Nordre Strømfjord region, petroleum geological studies, marine geophysical data acquisition and interpretation, stratigraphy and sedimentology of Lower Palaeozoic to Quaternary successions, and climate change.

Danmarks og Grønlands
Geologiske Undersøgelse (GEUS)
Geological Survey of Denmark and Greenland

Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

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