Report of Activities 1995

GEUS
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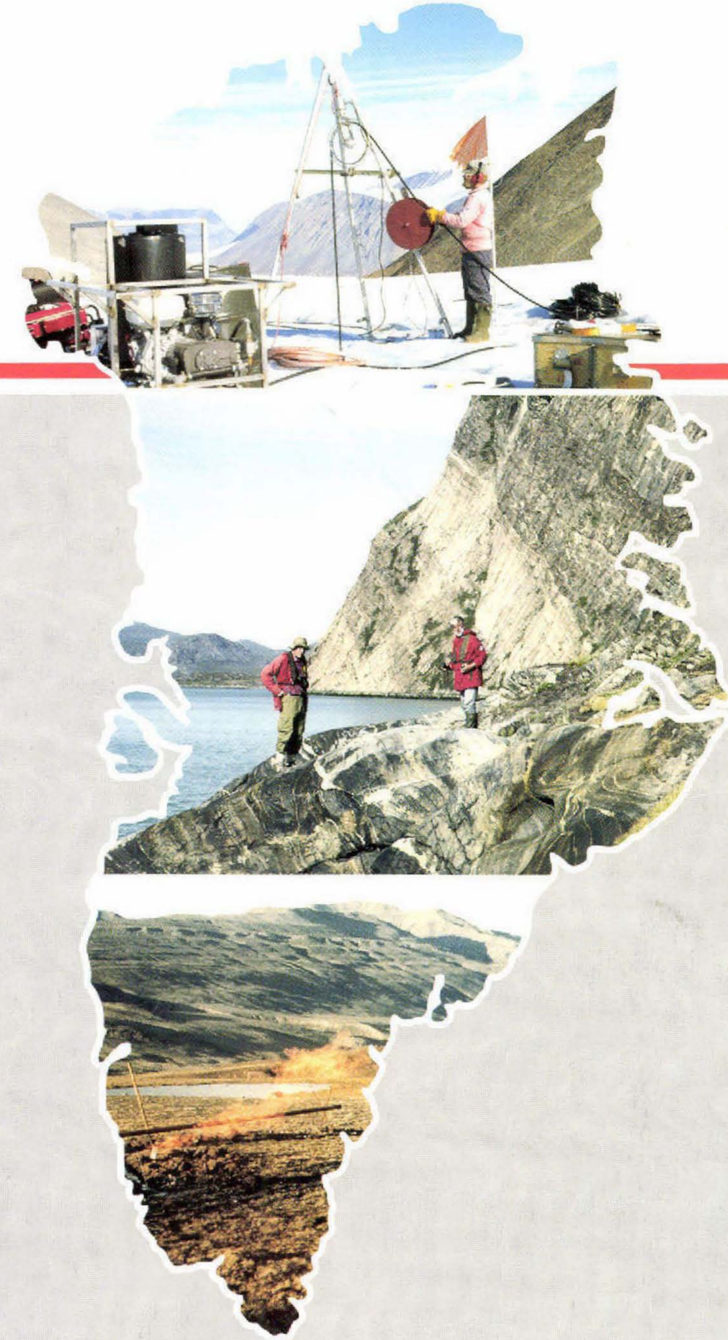

GGU

GRØNLANDS GEOLOGISKE UNDERSØGELSE

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GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN 172

Report of Activities 1995

edited by
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Cover photographs:

Greenland from north to south – aspects of Survey Greenland activities 1995.

Upper:

Hot water drilling for ice temperature measurements on Hans Tausen Iskappe, western Peary Land, North Greenland. This international glaciological project, partly funded by the Nordic Environmental Research Programme and by the European Union's third Framework Programme ENVIRONMENT, was launched in order to investigate present and past glacier dynamics in a region of high climatic variability and sensitivity. Photo: Henrik Højmark Thomsen.

Middle:

Studies of the orogenic evolution of the Nagssugtoqidian orogen in West Greenland were carried out by the Danish Lithosphere Centre in co-operation with the Survey and international research institutions. The photograph shows Archaean gneisses and Proterozoic supracrustal rocks at Kuup Akua. Photo: Jeroen van Gool.

Lower:

Flaring gas at well GANE #1. The first commercial oil exploration wells for almost 20 years were drilled in Greenland in 1995. Three wells were drilled by the Canadian company grønArctic on Nuussuaq, West Greenland, following systematic petroleum geological studies in the area during the past 3–4 years by the Survey. Photo: Kevin J. Bate.

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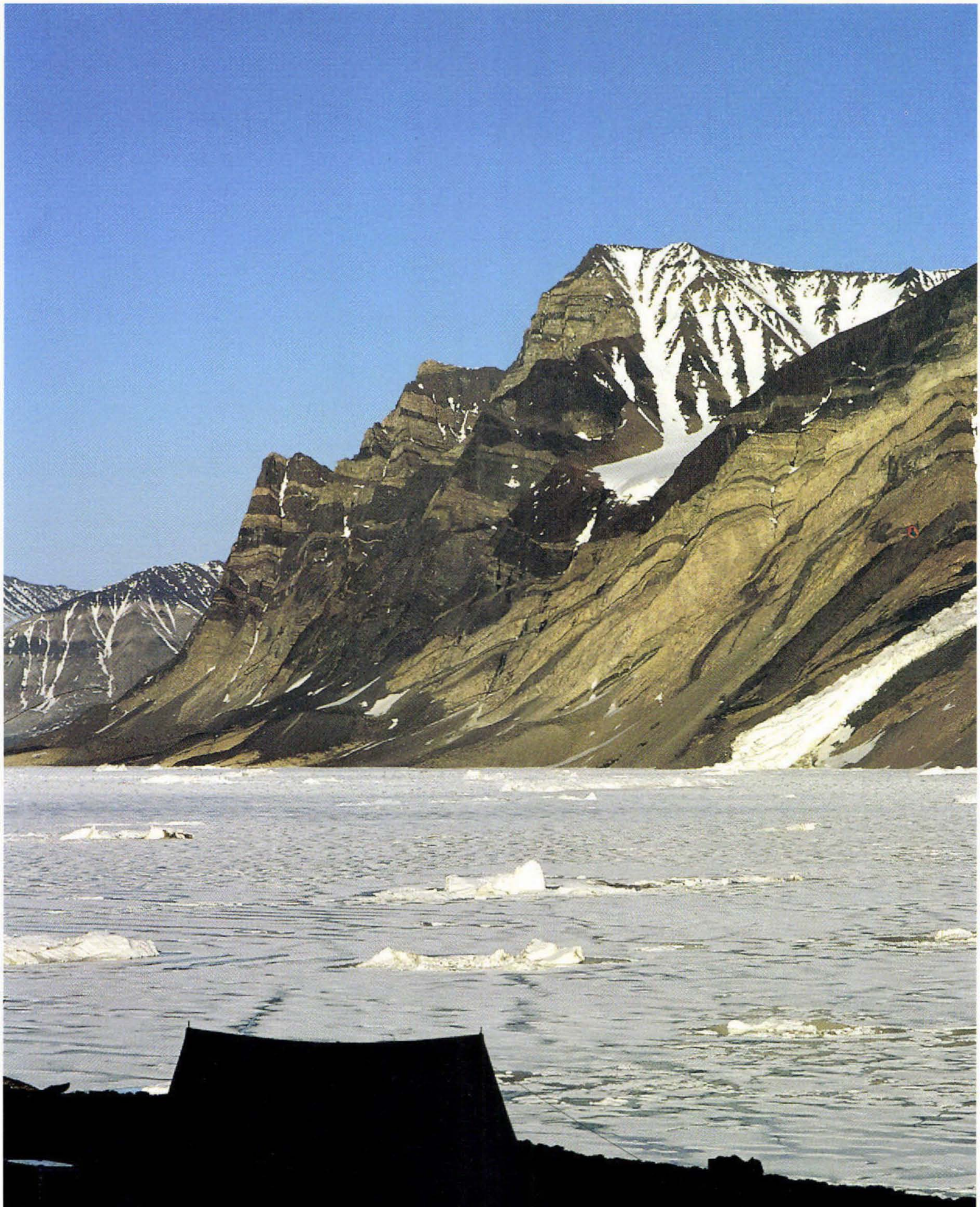
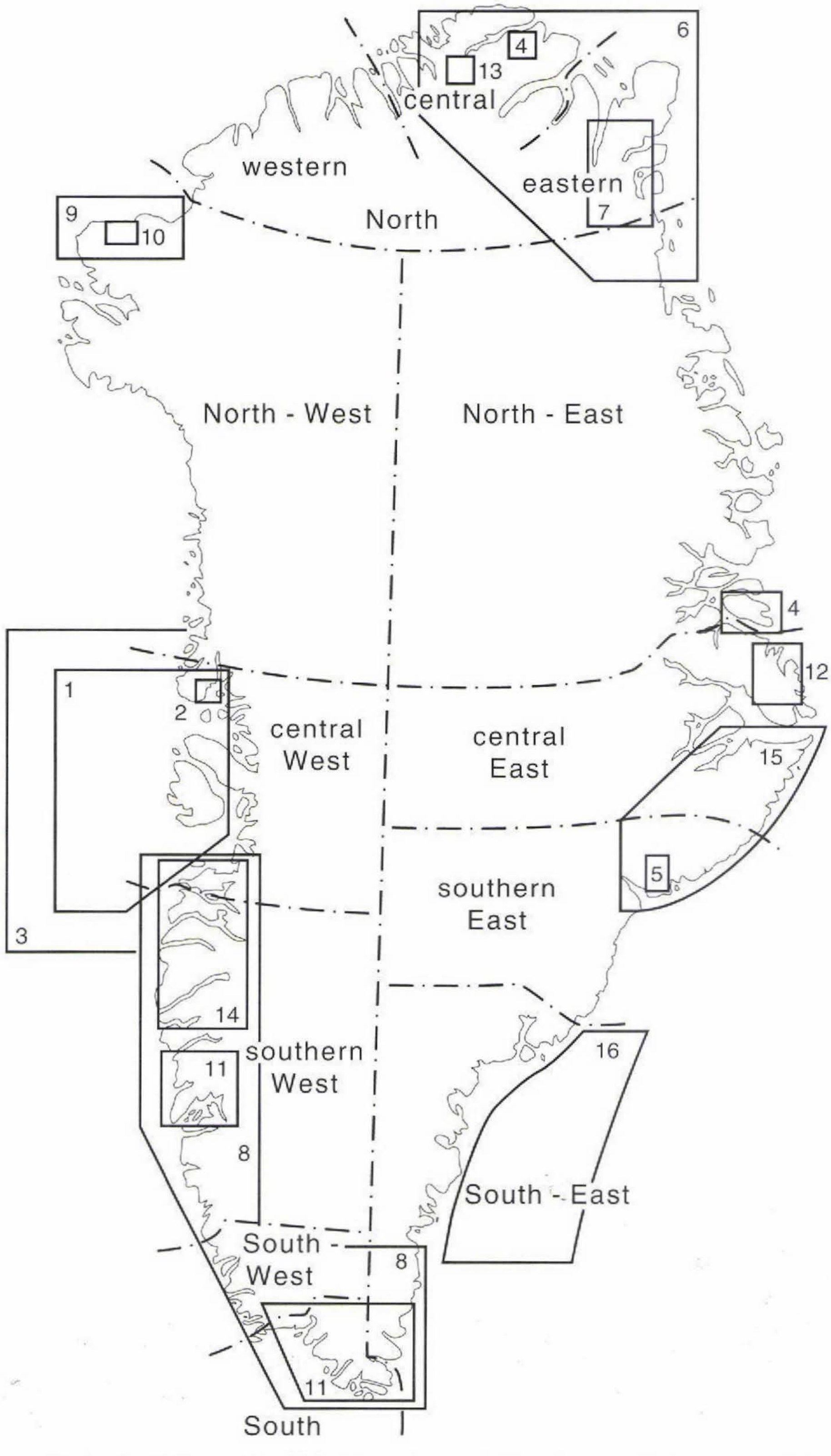


In 1995 the Surveys's three-year 1:500 000 field mapping campaign in eastern North Greenland was completed; the last remaining area to be compiled at this scale in North and North-East Greenland is now covered. The photograph shows a view of the Caroline Mathilde Alper at Ingolf Fjord, Kronprins Christian Land. Photo: Martin Sønderholm.



Locality map for contributions in this Report of Activities. Numerals locate individual papers in the table of contents on opposite page, although several papers dealing with the whole of Greenland are not located.

Contents

Bold numerals are allocated to papers which can be located on map opposite

GEUS – the new national geological survey

Martin Ghisler
Director

The Geological Survey of Greenland (GGU) was amalgamated with its larger brother – the Geological Survey of Denmark (DGU) – on 1st June 1995. The merger was approved by a unanimous decision of the Danish Parliament and accepted by the Greenland Home Rule Government. The new Survey, under the Ministry for Environment and Energy, comprises a staff of 360 persons, of which 100 come from the former GGU and 20 from the Danish Lithosphere Centre (DLC), a research centre formerly administratively linked to GGU and now linked to the new Survey.

The official name of the new Survey is 'Danmarks og Grønlands Geologiske Undersøgelse', in English 'Geological Survey of Denmark and Greenland', a long and somewhat cumbersome title in both languages which, for convenience, is abbreviated for many purposes to GEUS, derived from the Danish name for a geological survey (GEologisk UnderSøgelse). The tasks of the former GGU continue unaffected by the merger, and there have been no extraordinary reductions in funding or in staff numbers. During 1996 the majority of 'GGU' staff will move from their present building at the University of Copenhagen to the premises occupied by the former DGU 5 km away in NW Copenhagen.

A reorganisation of the Survey is effective from the 1 May 1996. The former GGU Department of Geological Mapping (including hard rock geochemistry and age dating) and the Department of Mineral Resources (now Economic Geology) continue virtually unchanged, whereas the 'GGU' glaciologists have become part of the new Department for Hydrology and Glaciology. The most significant changes in organisation are in the field of petroleum geology, where there was an overlap between the respective departments of the former GGU and DGU; in the new Survey there is no special petroleum geological department for Greenland. The petroleum division of the new Survey responsible for the geological activities relevant for hydrocarbon exploration and exploitation within the Kingdom of Denmark (Denmark, Greenland and the Faeroe Islands) comprises three departments: the Department for Stratigraphy, the Department for Geophysics and the Department for Reservoir Geology; analytical support is provided by the laboratories of the Geochemical Department. The Survey's administration and service functions have been fully integrated. The leadership of the Survey comprises a Managing Director, a Director and a Vice-Director.

The new Survey's premises in NW Copenhagen, situated in the office complex occupied by the former DGU, may only be temporary (3–4 years). A proposal to create a major GEOCENTRE in Copenhagen has been supported by the Ministry of Education, the Ministry of Research and Information Technology, the Ministry of Environment and Energy and the Prime Minister's Office. The proposed GEOCENTRE would comprise GEUS including DLC, together with the Geological Institute, Geological Museum and Geographical Institute of the University of Copenhagen, with the most likely site the 50 000 m^2 Øster Voldgade 10 complex already housing several of the involved institutes (as well as formerly GGU). Total expenses connected with renovation of the Øster Voldgade complex for the GEOCENTRE and relocation costs are estimated at 190 million Danish kroner. The final political decision on the establishment of a GEOCENTRE is ultimately linked to the overall National Research Strategy, and is expected to be taken before the end of 1996.

Advisory tasks

GEUS has continued its advisory tasks for the Mineral Resources Administration for Greenland with respect to regulation of exploration and – hopefully – exploitation activities. In addition GEUS collaborates in geoscientific tasks with the Minerals Office of the Greenland Home Rule Government in Nuuk, Greenland, where two senior geologists with experience in the fields of mineral exploration and petroleum geology are temporarily stationed.

On behalf of the Mineral Resources Administration for Greenland (MRA) GEUS carried out inspection visits to company drilling activities in the summer and autumn of 1995: grønArctic Energy Inc. on Nuussuaq, Platinova A/S at Citronen Fjord (Peary Land), Nunaoil A/S at Storø (Nuuk) and Kirkespirdalen (Nanortalik), and RTZ at Isua (Nuuk). In addition GEUS has carried out investigation and evaluation of the geological aspects of mineral resource developments in Greenland for the MRA with special emphasis on the petroleum geological aspects onshore and offshore West Greenland.

Publications and promotion of Greenland mineral and hydrocarbon potential

GEUS and the Mineral Resources Administration for Greenland continued their joint information services directed at the international oil and mining industry, in collaboration with the Minerals Office in Nuuk. This service includes presentation of geological results and information relevant to resource prospecting at meetings, symposia and exhibitions, as well as production of the newsletters *Ghexis* (oil and gas) and *Minex* (minerals). Efforts to make geological data, in the form of reports or digital data, readily accessible to companies have continued. Scientific results related to Greenland will be published by GEUS in the renamed '*Geology of Greenland, Survey Bulletin*' series (a continuation of the former GGU Bulletin series and incorporating the former GGU Rapport series); this will include an annual overview of Greenland activities. Preliminary results and data formerly published in the GGU Open File Series will in the future appear as '*Reports*' published by GEUS; these present data from Denmark, the Faeroe Islands and Greenland. Maps from Greenland will similarly be included in a single geodata map series comprising all types of maps of the Kingdom of Denmark.

Activities and funding

Geological, geochemical, geophysical and glaciological projects were carried out throughout Greenland in 1995. A total of 81 scientific and technical staff, including a number of guest scientists from institutions in Denmark and abroad, participated in GEUS expeditions. In addition the field activities of the Danish Lithosphere Centre comprised 65 participants (see separate review elsewhere in this volume). This volume presents an overview of the Survey's activities in Greenland during the past year. A short summary of the main field activities in 1995 is given below.

Funds for GEUS' Greenland activities in 1995 amounted to nearly 70 million DKK. Of this, 29 million Danish kroner came from external sources, the main contributor being the Danish National Research Foundation with approximately 50% for funding the activities of the Danish Lithosphere Centre.

Petroleum geology

The main activities in the petroleum geology field took place both onshore and offshore central West Greenland. On Svartenhuk Halvø a stratigraphic well was drilled to a depth of 1200 m in order to test the possibility for a marine source rock of mid-Cretaceous age. The well was drilled for GEUS by grønArctic Energy Inc. and funded by a special grant from the Greenland Home Rule Government and the Danish State.

Offshore GEUS carried out a reconnaissance seismic survey in the fjords and bays around Nuussuaq and acquired supplementary data on the shelf to the west of Disko. The latter was carried out with a 4.5 km streamer to test whether this could provide more information on the sediments underlying the basalts in this area. In addition seismic data were collected from an area west of Sisimiut, where the Kangâmiut-1 well encountered traces of hydrocarbons in 1976. A total of 3700 km of new seismic data was acquired in collaboration with Nunaoil A/S using the Danish Navy vessel *Thetis*, with special funding by the Greenland Home Rule Government and the Danish State.

Geological studies focusing on aspects of petroleum generating processes were initiated in North Greenland and central East Greenland as part of a three year programme supported by the Danish Natural Science Research Council. Petroleum geological investigations in the Wandel Sea Basin in eastern North Greenland with a view to evaluating the oil potential of areas offshore the northernmost segment of the East Greenland shelf were completed.

In the area of Kangerlussuaq in southern East Greenland outcrops of Cretaceous sediments were studied in co-operation with DLC and partly funded by Danish Oil and Gas Production A/S (DOPAS).

Geological mapping

The systematic 1:500 000 geological mapping programme in eastern North Greenland was completed after three field seasons working out of a base camp at Centrum Sø. Most activity was concentrated in the region 78°–81° N (map sheet no. 9), but activities supported spanned from Danmarkshavn in the south to Peary Land in the north. The project included structural, stratigraphic, and sedimentological studies within the Caledonian fold belt as well as in the foreland areas to the west. Some aspects of the field work were supported by the Carlsberg Foundation and the U.S. National Science Foundation.

In West Greenland studies of the Proterozoic Nagssugtoqidian fold belt were carried out by a DLC/GEUS group between Sisimiut and Disko Bugt. In East Greenland GEUS participated in the DLC-organised activities with studies of the basalt stratigraphy along Blosseville Kyst. GEUS joined the Ocean Drilling Programme offshore South-East Greenland (ODP Leg 163) with two scientists, one as co-chief scientist (from DLC).

Mineral resource investigations

The five-year airborne geophysical project (AEM 1994–98) financed by the Greenland Home Rule Government was continued. The survey area in 1995 covered Archaean terrain between Nuuk and Maniitsoq, from which 20 000 line km of magnetic and electromagnetic high quality data were collected and processed. Data are available to the mining industry at low cost (with a small handling fee) in order to encourage new prospecting activities.

An aeromagnetic survey financed by the Greenland Home Rule Government and the Danish State was flown in South Greenland; 70 000 line km of data were acquired over the ice-free areas of both the west and the east coasts of southern Greenland, including systematic coverage across the Inland Ice. On the west coast coverage reaches as far north as Ivituut. These data are also available at a modest charge.

In Inglefield Land in North-West Greenland follow-up ground work was carried out in continuation of the 1994 AEM geophysical survey. The investigations, funded by the Greenland Home Rule Government, comprised geological reconnaissance and geochemical sampling of stream sediments.

Ore geological investigations in eastern North Greenland, and especially around the Citronen Fjord zinc deposit, were initiated as part of a project focusing on ore forming processes in sedimentary basins, and including lead isotope studies. The project is supported by the Danish Natural Science Research Council.

Glaciology

Glaciological investigations in the field of climatic research have been continued by GEUS in close co-operation with the Alfred-Wegener-Institute, Bremerhaven, Germany, and the Niels Bohr Institute at the University of Copenhagen, and with the participation of scientists from several countries. The investigations, which included drilling of a small ice cap, were funded by the European Union, the Nordic Council of Ministers, the Danish Natural Science Research Council and the Danish Polar Center.

Three areas were investigated: Hans Tausen Iskappe in Peary Land, the ice margin in southern Kronprins Christian Land and the glacier Storstrømmen west of Danmarkshavn.

Publications

In 1995 a new *Geological Map of Greenland* at a scale of 1:2 500 000 was published, which included for the first time the geology of offshore areas. A geological map of part of the Disko Bugt area in West Greenland at 1:100 000 (Ataa 69 V.3N) was also printed. A new volume in the GGU *Thematic Map Series* containing a set of 63 thematic maps at 1:1 000 000 (mainly compilations of geochemical data) was released covering the area between Paamiut and Buksefjorden. One volume in GGU's *Rapport Series* (22 articles) and fourteen numbers in GGU's *Open File Series* were also issued. As a consequence of research activities in Greenland 24 articles were published in international scientific journals. A complete list of 1995 publications is given at the end of this volume.

Organisational bonus through staff rejuvenation: Greenland – Australia exchange

Peter R. Dawes and Cees P. Swager

Advances in geoscientific research are more than ever before dependent on international teamwork. Concurrently with this increased co-operation, geological surveys the world over are becoming more and more international in outlook. Stimulated by government initiatives, modern geological surveys, both national and state, are committed towards greater customer focus. Not only are work programmes now specifically designed to encourage commercial investment by directly meeting the needs of industry, but geological surveys are widening their scope and image by undertaking activities abroad. Apart from the scientific advantages of international co-operation and the added incentives of staff training and development, involvement in foreign projects is arguably part of a Survey's political responsibility in assisting developing countries.

This introductory statement applies equally well to the newly constituted Geological Survey of Denmark and Greenland based in Copenhagen, as to the Geological Survey of Western Australia, 15 000 km away in the southern hemisphere, with headquarters in Perth. Survey activities abroad range in scale and type from the engagement of geoscientific teams carrying out specific tasks on contract, with the periodic stationing of personnel abroad, to the technical exchange of expertise and advice on a personal level.

This paper deals with an example of a short-term staff exchange (9 months) between Copenhagen and Perth, and the benefits gained, both on organisational and individual levels. The authors, as participants in this exchange, were engaged in their host country on projects involved with the study and mapping of Precambrian complexes (Guj, 1995). Thus, the theme of this paper is mainly concerned with Precambrian geology, although the general premises discussed may equally apply to other geological fields.

The 1994–95 exchange: field season, conditions and survey reorganisation

The exchange took place between June 1994 and April 1995. Built into the programme was one season's field work, participation in a team project, with enough time available to work on and write up the main results. Although dealing with regions in opposite hemispheres, the normal field seasons in the two lands are broadly concurrent. Both are constrained by the climate: in Greenland by the cold, snow and darkness of winter; in Western Australia by the heat of summer.

Important premises behind the exchange were that the participants should be permanent Survey employees with several years seniority and of broadly similar status. Conditions were thus optimal to ensure that the expertise offered to both organisations would be comparable, and that the experiences gained would be transferred back to the home organisation.

It so happened that political initiatives determined that in 1994–95 the geological surveys in Copenhagen and Perth were undergoing change. During the period of the exchange, the Geological Survey of Greenland was involved in discussions about the merger with the larger Geological Survey of Denmark and about the future relationship to the Greenland Home Rule Government (Ghisler, 1995). On the other hand, the Geological Survey of Western Australia was undergoing reorganisation and expansion. This was the result of the incorporation of the cartographical mapping branch, and the addition of contract staff into new programmes introduced through extra governmental funding which aimed to stimulate investment in exploration (Guj, 1994). These developments gave a much closer insight into the organisation of 'state-run geology' in our host country than otherwise would have been the case.

Greenland and Western Australia: similarities and contrasts

Greenland and Western Australia have a comparable size and geological make-up. Western Australia has an area of 2.5 mill. km^2 against Greenland's 2.2 mill. km^2 (Fig. 1), and both regions have a fairly complete geological column from the Precambrian to Cainozoic. Permanent ice covers about 80% of Greenland; some 90% of Western Australia has a deeply weathered regolith cover. Of particular note is the fact that the geological history of both countries goes back to the earliest Archaean with the Nuuk region of West Greenland and the Yilgarn Craton of Western Australia (Fig. 1) having for many years competed for the tag of sporting the world's oldest rocks; this position is now held by the Slave province of Canada with the 4.0 Ga Acasta gneiss.

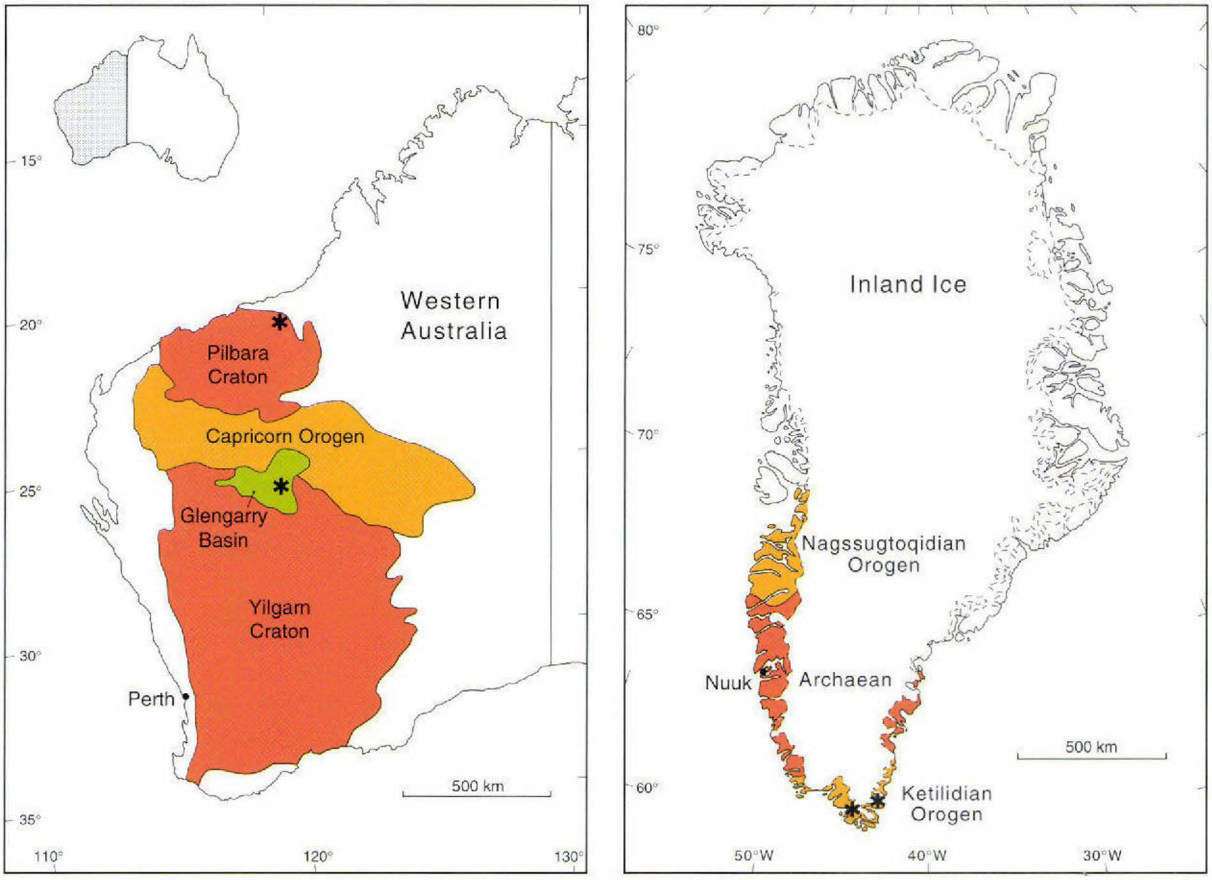


Fig. 1. Location maps of Greenland and Western Australia at the same scale. Stars locate the field areas studied during the exchange.

The Precambrian geology of Greenland and Western Australia have been the subject of comparative studies (e. g. Nutman, 1991), and both regions have contributed to the understanding of the evolution and assembly of Precambrian gneiss terranes and in unravelling the Earth's earliest history. Early to Late Proterozoic sedimentary and volcanic successions are also well represented in both countries. Recent research suggests that the Precambrian crust of Greenland and Western Australia evolved spatially much closer than the present-day geography might suggest. Based on the similar Proterozoic crustal evolution and metallogeny, recent supercontinent reconstructions favour the amalgamation of Laurentia and Australasia, with North America being juxtaposed off eastern Australia (Hoffman, 1991; Young, 1992).

Late Proterozoic glacial deposits are preserved in both countries, and followed by thick Phanerozoic successions in which Palaeozoic, Mesozoic and Cainozoic sequences are present. These sequences occur both as undeformed platform cover and within orogenic belts. In Western Australia Phanerozoic rocks compose more than 50% of the country; in Greenland about 30%.

Apart from the obvious geographical differences between Greenland and Western Australia – ice and an arctic climate versus a laterite-covered arid region – a fundamental difference concerns the role played by geology in the economic development of the two lands. Considering their similar geological make-up, this is enigmatic. Mining is an important part of everyday life and the backbone of Western Australia's economy. Of the wide range of commodities mined – gold, iron ore, nickel, bauxite/alumina, titanium minerals, salt, diamonds, petroleum/gas, coal, manganese, base metals (just to name the most important) – many represent major sources on a world scale. In stark contrast, Greenland, at the present time, has no mining industry. In the light of this sombre difference, Australian expertise must be welcome in any exploration and mineral assessment in Greenland.

Other notable geo-contrasts between Greenland and Western Australia are in physiography, rock exposure and commercial exploration. In Western Australia, where the majority of the landscape is flat to moderately undulating, the bedrock is poorly exposed and mostly concealed by a variable regolith and woodland to scrub vegetation

(Fig. 2A). The rocks are, however, generally well mineralised and, as a requisite for a thriving mining industry, there is a high level of mineral exploration. In contrast, Greenland with its rugged, in places alpine, topography and indented coast and deep fjords offers some of the best rock exposures in the world, where ice-cleaned surfaces reveal spectacular large-scale geological relationships and clear rock detail (Fig. 2B). However, comparable rock formations to those of Western Australia apparently contain scarce mineralisation (at least at outcrop level) and commercial exploration is at a relatively low level.

Mineable deposits, both near-surface and blind ore bodies, are still being discovered in Western Australia in both poorly explored areas and in the historical mining districts that have been exploited since the last century. Western Australia, unlike Greenland, is covered by standard geophysical maps; a requisite for modern exploration. The well-exposed Greenland outcrops, classified as barren by first-time mapping and exploration programmes, may prove otherwise when studied in the next round of exploration that includes probing the sub-surface. Seen against the claim of Australian metallurgists that Western Australia has still underexplored, even virgin, territory (Guj *et al.*, 1995), the mineral exploration of Greenland is in its early infancy.

Exchange potential

Addition of foreign expertise must be a benefit to any geological organisation; when in the form of an exchange there are incentives to be gained through the new experiences filtered back to the home organisation by mutual training of staff. Seen against the background discussed above – similar geology but basic differences in physiography, rock exposure and commercial exploration – staff exchanges between Greenland and Australia have interesting potential.

Greenland geologists, experienced in working with well-exposed geology and continuous outcrop, can assist in the interpretation of complex bedrock geology in areas of sporadic to extremely poor outcrop. Specific topics might be, for example, the relationships between granites, gneisses, migmatites and supracrustal rocks, or the intricate facies associations of sedimentary basins. In Greenland the nature of granite-greenstone, infracrustal-supracrustal and lithostratigraphic relationships are often determinable directly in outcrop, and the passage from granite and sediment into, respectively, orthogneiss and paragneiss can often be walked out on the ground. In some regions, the boundaries of orogenic belts are there to be seen and photographed; for example, the now classical southern boundary of the Early Proterozoic Nagssugtoqidian Orogen of West Greenland, where the progressive deformation and metamorphism of country rocks and basic dykes can be followed in ice-polished fjord walls (Ramberg, 1949).

Conversely, Australian geologists, with experience in mapping mineralised rocks and in metallogenetic modelling, are well equipped to contribute to the evaluation of the mineral resource potential of Greenland's presently non-productive terrains. Are these terrains really less mineralised, or simply underexplored? How far is the comparatively rare mineralisation due to depth of exposure? Based on present knowledge of mineralisation styles, in which direction should renewed exploration in Greenland take?

In terms of training, Greenland geologists would gain experience in the standard use of geophysical techniques and satellite imagery in the mapping of concealed bedrock, as well as gaining insight into the wide range of styles of mineralisation present in Australian rocks. On the other hand, geologists returning to the mapping of regolith-covered terrains, would have first-hand knowledge of continuous structure and rock relationships, seen potentially in both horizontal and vertical planes. In many parts of Greenland, exposures with a relief of 1000 m are common; in parts of East and South Greenland relief is 2000 m or greater (Fig. 2B). In such areas there is ample scope to integrate detailed structural observations made on a local scale with rock types and structures seen in large-scale continuous sections. This experience is of some relevance when confronted only with data from restricted outcrops (as is often the case in Western Australia, Fig. 2A) from which regional interpretations have to be made.

Field work in Australia and results

Field work by PRD was on two projects, as well as participation in excursions to operational mines. The main field work was conducted between July and October in four periods, with intervals back in the office in Perth. Travel in the field was by four-wheel drive vehicle and for most of the time with field assistant Eugene Carew.

The Glengarry project

This project involves the 1:100 000 mapping of Early Proterozoic sedimentary and mafic volcanic and subvolcanic rocks of the Glengarry Basin on the northern margin of the Yilgarn Craton (Fig. 1). The rocks were deformed and metamorphosed at low grade during the collision of the Yilgarn and Pilbara Cratons that formed the Early Proterozoic Capricorn Orogen. The Glengarry project, initiated late in 1993 as one of several new projects requested by industry, has the aim of mapping the entire Glengarry Basin (Pirajno, 1995). As part of a team of five, PRD's responsibility was the mapping and compilation of the northern part of the Mount Bartle 1:100 000 sheet, producing an explanatory text, and contributing to a new stratigraphic framework for the Glengarry region (Dawes & Le Blanc Smith, 1995; Grey *et al.*, 1995; Dawes *et al.*, in press).

The Yarrie - Shay Gap project

This project comprised a 10-day investigation of Archaean granite-greenstone contacts in the region around the iron-ore opencut mines at Yarrie and Shay Gap in the north-eastern part of the Pilbara Craton (Fig. 1). Accompanied by Survey geologist R. H. Smithies, the work was carried out in co-operation with geologists from the Broken Hill Proprietary Co. Ltd (BHP) mine at Yarrie. The field work established that the contact between granite batholiths and the banded iron-formation of the Gorge Creek Group represents an unconformity and not, as previously thought, a case of granite intruding the sedimentary succession. The documented hiatus, probably of Early Archaean age, has regionalz implications for the interpretation of other granite-greenstone contacts elsewhere in the north-eastern Pilbara (Dawes *et al.*, 1995a, b; Smithies & Dawes, in press).

Field work in Greenland and results

Field work undertaken by CPS was part of the SUPRASYD project investigating the Ketilidian Orogen of South Greenland. In 1994, work was concentrated on both the south-east and south-west coasts of Greenland (Fig. 1). The field work, carried out in a 7-week period in July and August, was by 2-man teams supported by helicopter. Eight geologists took part in the field operation (Garde & Schønwandt, 1995).

The SUPRASYD project

This project, started in 1992, is part of the Survey's long-term mineral resource evaluation programme (Dawes & Schønwandt, 1992). The main aim of the project is a reassessment of the tectonic setting and mineral potential of the Early Proterozoic Ketilidian Orogen, particularly the lesser known and more inaccessible region along the south-east coast of Greenland. The project field work commenced in 1992 (Nielsen *et al.*, 1993).

Mapping work on the south-east coast of Greenland by CPS, accompanied by Tom Frisch, was on the Lindenow Fjord 1:100 000 sheet and placed emphasis on structural analysis of gneisses and high-grade supracrustal rocks. This contributed to the compilation of a provisional 1:100 000 map with explanatory notes (Swager *et al.*, 1995). On the south-west coast of Greenland a shorter period was spent, together with Bjørn Thomassen, in mapping and investigating the ore geology and mineral potential of migmatitic supracrustal rocks adjacent to the Julianehåb batholith. An alternative plate tectonic model for the Ketilidian Orogen emerged from the work, in which the well-known gold mineralisation is related to shear zones active in a back-arc basin (Chadwick *et al.*, 1995; Stendal & Swager, 1995).

Conclusions

The exchange in focus here is a small example or test case of what is possible to achieve on short-term work abroad. Participation in the exchange presented a chance to undertake geological research free from administrative duties, on a different supercontinent (Laurentia versus Gondwana), with new colleagues in a different team framework, and under a complete contrast of climatic, physiographic and logistic conditions. While the major processes of Precambrian geology and the resultant make-up of the shield in Greenland and Western Australia are largely comparable, the different physical conditions provide a real challenge on how to tackle exploration and mapping. The experiences of geological mapping in Greenland and Australia are ideally suited to assist in solving each others specific geological problems.

Greenland and Western Australia have equally diverse geology; Western Australia has diverse mineral productivity as well. The geological surveys of both countries are committed to mapping, recording and interpreting the geology of their territories, and bringing this information effectively to industry and the people who need it. With the vivid contrast in status of mineral exploration and mining in the two countries, it has been rewarding to see how these aims are being achieved by our host organisations.

Final comment

The final comment records the satisfaction of gaining further geological training and experience with a foreign organisation, without the necessity of changing place of permanent employment. Personal rejuvenation is an important aspect of staff development and job satisfaction, and a recommended part of modern personnel management.

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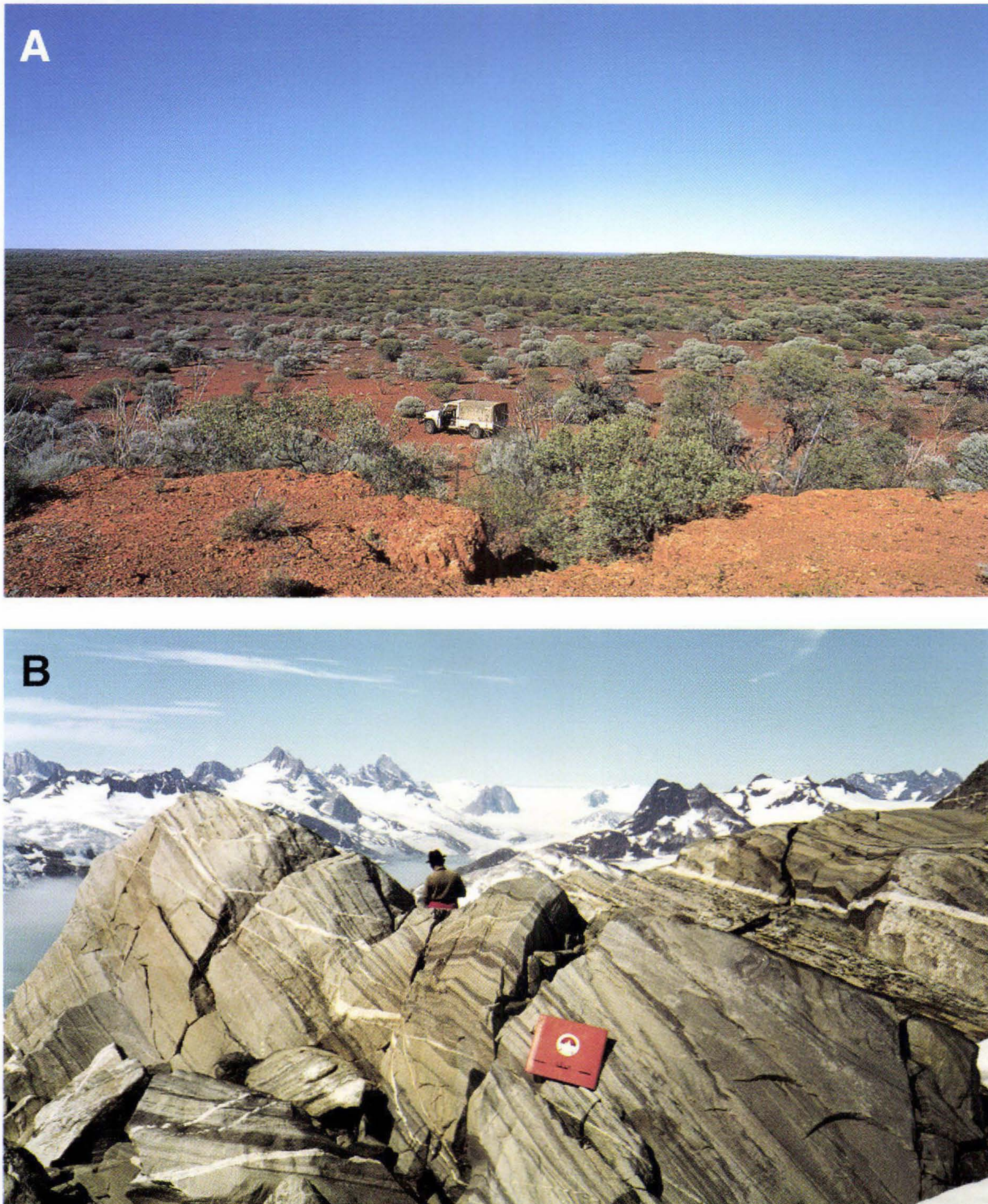

Fig. 2. Contrasts in topography and rock exposure in the Early Proterozoic of Western Australia and Greenland. A: Brown laterite-covered bush landscape of the Glengarry Basin, with main outcrops in low-relief breakaway scarps as in foreground and on the horizon. Kimberley Range, Meekatharra District. Photo: P. R. Dawes, October 1994. B: Clean exposures and alpine topography in the Ketilidian orogenic belt. Psammitic metasedimentary rocks in the foreground; in the background, great relief with the most prominent peak more than 2500 m a.s.l. View is south-west across Danell Fjord. Photo: Bjørn Thomassen, July 1994.

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Continued geophysical and petroleum geological activities in West Greenland in 1995 and the start of onshore exploration

Flemming G. Christiansen, Kevin J. Bate, Gregers Dam, Christian Marcussen and T. C. R. Pulvertaft

The 1995 summer season saw continued petroleum activities in West Greenland, both onshore and offshore. The activities took place both as major geological and geophysical projects led by the Geological Survey of Denmark and Greenland (GEUS) and financed jointly by the Government of Greenland, Minerals Office and the Danish State, and as a new commercial exploration programme with the Canadian oil company grønArctic Energy Inc. as operator.

During the past 3–4 years the attitude that the onshore Nuussuaq Basin is mainly of interest as a source of important data for evaluating the offshore exploration potential has changed to the view that it has considerable exploration possibilities of its own (Christiansen *et al.*, 1995). In addition to major systematic studies of the sedimentology, stratigraphy and organic geochemistry of the Cretaceous and Tertiary succession (e.g. Christiansen *et al.*, 1996; Dam & Sønderholm, 1994, in press; Nøhr-Hansen, 1993, 1994a, b, in press) a number of encouraging breakthroughs have been important in focusing on local exploration possibilities:

- discovery of surface oil seeps in 1992–94 (an area of at least 8 × 5 km) and in cores from the Marraat-1 drill hole on southern Nuussuaq in 1993 (Christiansen, 1993; Christiansen *et al.*, 1994a, b, 1995);
- discovery of wet gas in 1994 during drilling for hard minerals at Serfat on the north coast of Nuussuaq (Dam & Nøhr-Hansen, 1995);
- documentation by refraction and reflection seismics in 1994 that the sedimentary succession under at least part of Nuussuaq is much thicker (more than 8 km) than previously expected (Christiansen *et al.*, 1995).

In the areas offshore West Greenland new seismic data acquired by the Geological Survey of Greenland (GGU) in 1990–92 and by Nunaoil A/S in 1994 have led to a greatly improved understanding of the regional structure of the sedimentary basins and revealed new plays for petroleum exploration (see reviews by Chalmers *et al.*, 1993, 1995). This has especially been the case for the Fylla area (Fig. 1) where the existence of large structures with direct hydrocarbon indicators in the form of flat-spots have attracted the attention of industry (Bate *et al.*, 1994, 1995). However, the exploration possibilities are not restricted to the Fylla area, and several recent studies have provided interesting results that could be important guides for exploration in the coming years:

- interpretation of seismic data west of Disko suggesting that subvolcanic plays could be explored (Whittaker, 1995, this report; Whittaker *et al.*, 1996);
- reinterpretation of the log and other data from the Kangâmiut-1 well indicating that wet gas was encountered but never properly tested (Bate, 1995, in press);
- identification of large, but complex, transpressional structures in the area around the Ikermiut-1 well that could provide traps for hydrocarbons (Chalmers *et al.*, 1995).

The many encouraging results and ideas on exploration possibilities both onshore and offshore West Greenland encouraged the Government of Greenland, Minerals Office and the Danish State to provide funding for major projects related to petroleum exploration. The projects carried out in 1995 include seismic acquisition in the fjords of the Disko – Nuussuaq area and the offshore area west of Disko (DiskoSeis 95), seismic acquisition off southern West Greenland (IkerSeis 95, KangaSeis 95, ExtraSeis 95), drilling of a stratigraphic well on Svartenhuk Halvø, and a detailed study of the cores drilled by grønArctic Energy Inc. during their exploration.

Seismic programme

The seismic programme was carried out with Nunaoil A/S as operator using the Danish Navy vessel *Thetis* which has been adapted to accommodate seismic equipment. Acquisition took place in the period 23 June – 3 August 1995 and a total of 3745 km seismic data were collected (Fig. 1). The data are presently being processed by Robertson Research International Limited (formerly Simon Petroleum Technology) (DiskoSeis 95) and Spectrum Energy and Information Technology (IkerSeis 95, KangaSeis 95, ExtraSeis 95).

DiskoSeis 95

The main aim of the DiskoSeis 95 survey was to document thick sedimentary successions in the fjords and bays

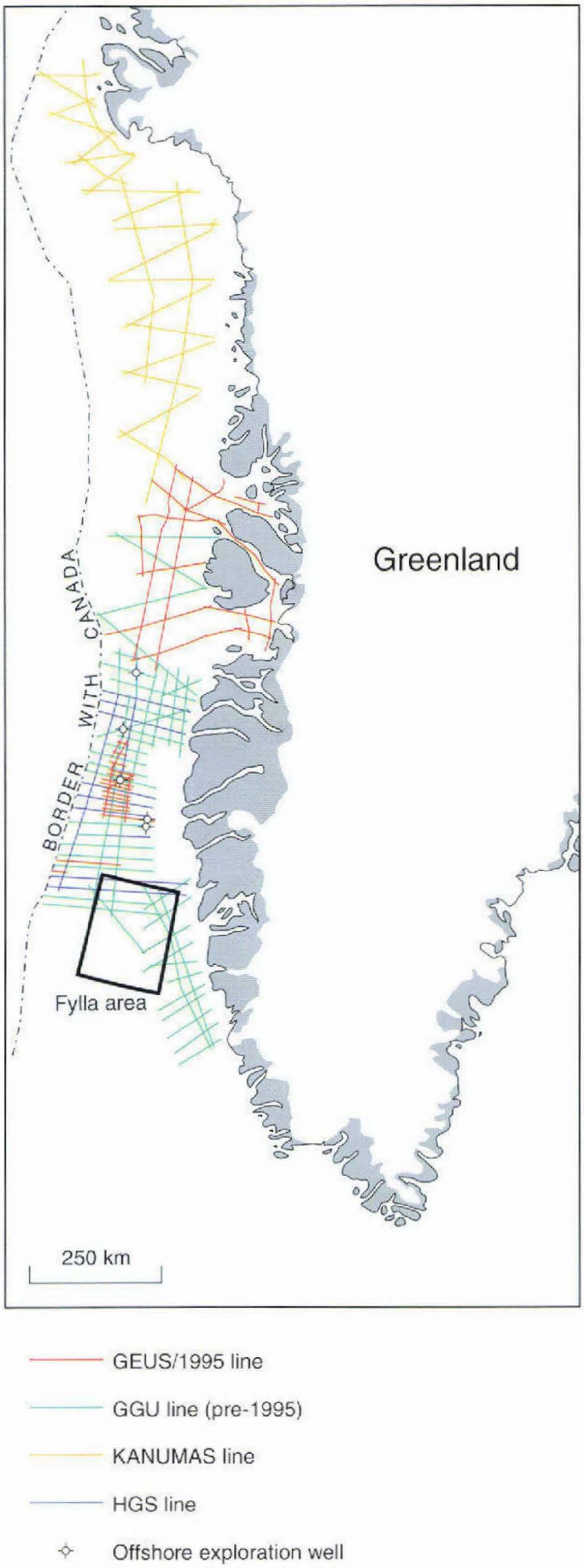

Fig. 1. Location of offshore seismic lines in West Greenland.

around Disko and Nuussuaq and to study the structural development of the Nuussuaq Basin (Figs 1, 2). Very thick sedimentary successions in half-grabens have previously been documented offshore North-West Greenland (see Whittaker & Hamann, 1995) and along the south coast of Nuussuaq (Christiansen *et al.*, 1995), and are also indicated by significant negative anomalies on newly acquired satellite and airborne gravity data in the Disko Bugt area.

The DiskoSeis 95 survey was also extended to areas of possible interest for exploration west of Disko (Figs 1, 2) to test if the use of a longer streamer (4.5 km) could provide more information on the sediments underlying the volcanics than observed by Whittaker (1995) in his study of older seismic data.

Table 1. Technical data from the grønArctic well GANE #1

Well name:	grønArctic Nuussuaq Eqalulik #1 (GANE #1)
Operator:	grønArctic Energy Inc., Calgary, Alberta, Canada
Drill contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada
Locality:	Aaffarsuaq valley, Nuussuaq, West Greenland
Co-ordinates:	70°28′25″ N, 54°00′40″ W
Elevation:	114 m a.s.l.
Well spud date:	10 July 1995
Termination:	6 August 1995
Rig type:	Longyear 44 diamond core drill, adapted mining rig
Total depth:	707 m, ~100% core recovery
Hole diameter:	0–202 m: 96.0 mm (HQ rods),
	202–510 m: 75.8 mm (NQ rods),
	510–707 m: 60 mm (BQ rods)
Core diameter:	0–202 m: 63.5 mm,
	202–510 m: 47.6 mm,
	510–707m: 36.5 mm
Status:	Plugged and abandoned
Main target:	Structural Marraat-type prospect (oil generated from Tertiary deltaic source rock, Tertiary or Cretaceous sandstone reservoir)
Formations drilled:	Lower Tertiary volcanics (500 m), Lower Tertiary and ?Cretaceous siliciclastic sediments (207 m)
Hydrocarbons:	Some oil bleeding from core in volcanics; some oil impregnation in sandstones, some gas under pressure in sandstones

KangaSeis 95, IkerSeis 95, ExtraSeis 95

The plan for the KangaSeis 95 survey was mainly to acquire a more dense grid of seismic data over the Kangâmiut Ridge. The Kangâmiut-1 well, drilled in 1976 by Total Grønland Olie on the western flank of this ridge, recorded a wet gas kick at a depth of 3694 m (Bate, 1995). All planned seismic lines were acquired.

It was also hoped to acquire more data in the area west of the Ikermiut-1 well where complex compressional structures are known but where the seismic coverage is limited. However, the *vestis* (Danish for 'west ice') had not completely retreated from the area in the period when *Thetis* was available, so only a limited part of the survey was carried out. As a consequence of this change of plans some additional data (ExtraSeis 95) were shot farther to the south over a little known area west of the Fylla structural complex (Fig. 1).

Drilling of stratigraphic well on Svartenhuk Halvø

The Umiivik-1 stratigraphic slim-core well on Svartenhuk Halvø was drilled in the period 21 August – 15 September 1995. GEUS was operator for the well which was drilled by grønArctic Energy Inc. under the terms of a turn-key contract with the Government of Greenland, Minerals Office.

The main aim of the bore hole was to obtain information on the sedimentology and stratigraphy of the basal part of the marine Upper Cretaceous mudstones, and if possible to document evidence for an oil-prone source rock of Cenomanian – Turonian age. The well reached the planned depth of 1200 m after having penetrated a thick succession of marine shales with several thick dolerite dykes and sills. The presumed underlying non-marine succession was not reached. Results from the Umiivik-1 well are presented separately by Bate & Christiansen (this report).

Drilling of commercial wells (grønArctic Energy)

In the summer of 1995 the first commercial oil exploration wells for almost 20 years were drilled in Greenland with the Canadian company grønArctic Energy Inc. as operator. In May 1995 grønArctic Energy Inc. and Platinova A/S were granted an exclusive exploration licence for a 1692 km² large area covering western Nuussuaq (Fig. 2). grønArctic began their exploration programme with the drilling of three slim-core holes to depths between 400 and 900 m.

Detailed results from the drilling are at present confidential but general information has been released by grønArctic Energy Inc. and the Mineral Resources Administration for Greenland (see Tables 1–3). GEUS carried out the well site geological description and sampling, and is carrying out an analytical programme for grønArctic Energy Inc. Results from this programme may be released after 1 April 1997.

GANE #1 and GANK #1

These wells are situated in the Aaffarsuaq valley, approximately 10 and 15 km respectively east-south-east of GGU's Marraat-1 well (Figs 2, 3). The main target in both wells was a Marraat type play, i.e. Maastrichtian – Lower Paleocene channel or turbidite sandstone reservoir with a deltaic source rock of similar age, within a structural or stratigraphic trap. Both wells are situated in a little known area some kilometres south-east of the area where oil has previously been documented at the surface (Christiansen *et al.*, 1995, 1996).

Table 2. Technical data from the grønArctic well GANT #1

Well name:	grønArctic Nuussuaq Tunorsuaq #1 (GANT #1)
Operator:	grønArctic Energy Inc., Calgary, Alberta, Canada
Drill contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada
Locality:	Tunorsuaq valley, Nuussuaq, West Greenland
Co-ordinates:	70°42′70″ N, 53°36′02″ W
Elevation:	~440 m a.s.l.
Well spud date:	14 July 1995
Termination:	11 August 1995
Rig type:	Longyear 50 diamond core drill, adapted mining rig
Total depth:	901 m, ~100% core recovery
Hole diameter:	0–249 m: 96.0 mm (HQ rods), 249–901 m: 75.8 mm (NQ rods)
Core diameter:	0–249 m: 63.5 mm, 249–901 m: 47.6 mm
Status:	Plugged and abandoned
Main target:	Structural Serfat-type prospect (oil/condensate generated from mid-Cretaceous source rock, marine Upper Cretaceous or non-marine Lower Cretaceous sandstone reservoir)
Formations drilled:	Lower Tertiary and Upper Cretaceous siliciclastic sediments (901 m)
Hydrocarbons:	Some gas under pressure in many sandstone units

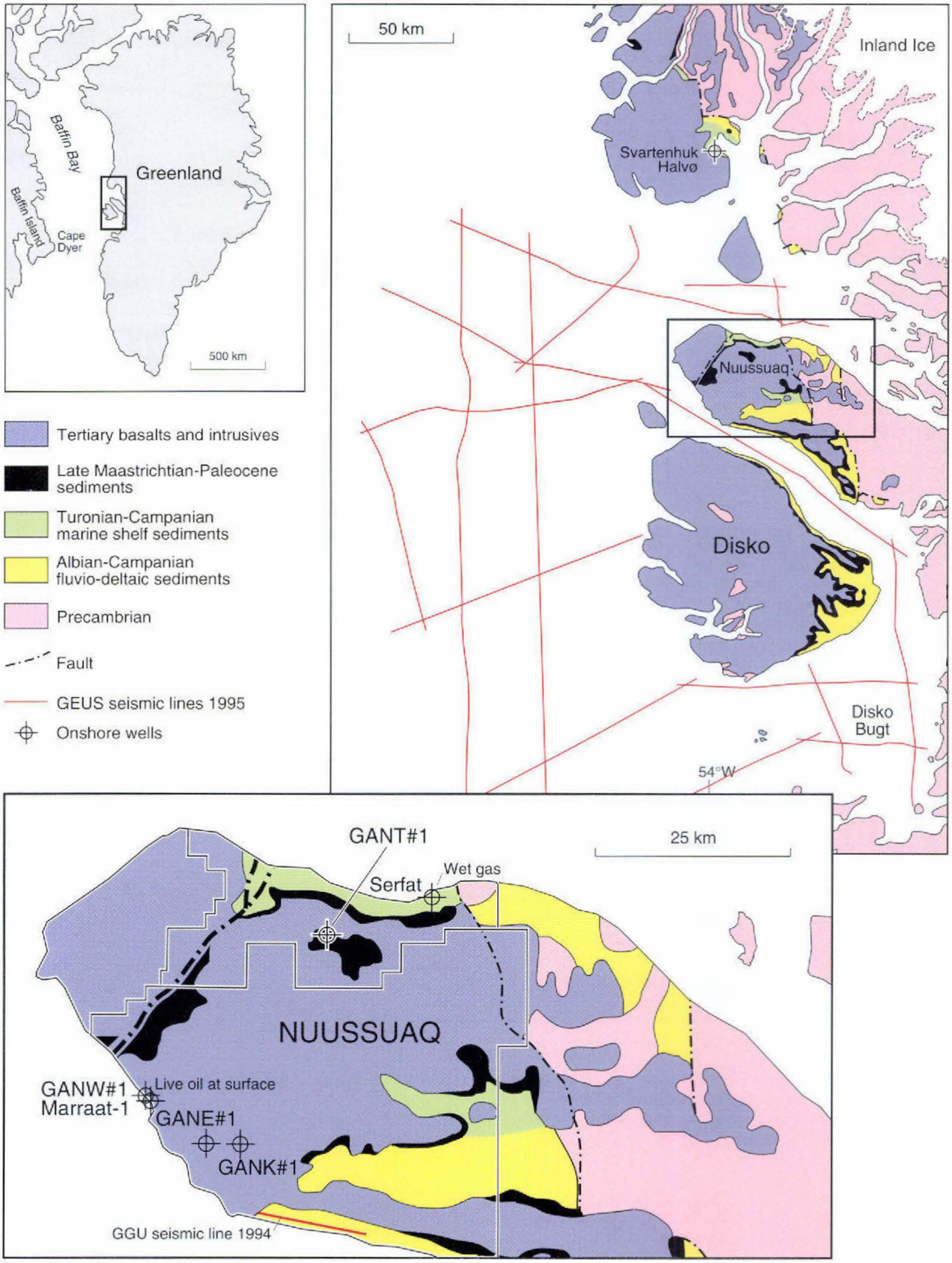

Fig. 2. Map of the Disko – Nuussuaq – Svartenhuk Halvø area showing positions of 1995 offshore seismic lines, wells and grønArctic's licence areas.

Fig. 3. GANE #1 drill site in the Aaffarsuaq valley, Nuussuaq.

Both wells were sited on hyaloclastic breccias, the base of which was penetrated at 497 m in GANE #1 and at 115 m in GANK #1. Oil was identified bleeding from the cores at several levels in the volcanics in which traces of oil are generally common. In the underlying Maastrichtian? – Tertiary sedimentary succession gas under pressure as well as oil impregnation was encountered (Fig. 4). Drilling was terminated at depths of 707 m and 398 m, respectively (Tables 1 and 2).

GANT #1

This well is situated in the Tunorsuaq valley (Fig. 2), where a Cretaceous – Tertiary succession similar to that known from the north coast of Nuussuaq is exposed. The main target was a structural play, with marine Cretaceous sandstones as the reservoir unit and an inferred mid-Cretaceous oil-prone source rock. The well was clearly inspired by the discovery of wet gas in a mineral exploration drill hole at Serfat on the north coast of Nuussuaq in the summer of 1994 (see Dam & Nøhr-Hansen, 1995).

GANT #1 was sited very close to the Cretaceous–Tertiary boundary and penetrated a succession of Upper Cretaceous marine sediments. The well reached a depth of 901 m and documented a number of sandstone layers with gas under pressure (Table 3).

Future exploration

Although none of the wells reached the planned depth of 1000 m, grønArctic Energy Inc. is reported to be very encouraged by the results and plans further drilling with a conventional oil exploration rig in 1996. GrønArctic Energy Inc. has applied for additional acreage on Nuussuaq adjacent to its present licence area. Furthermore grønArctic Energy Inc. is negotiating a new exploration licence covering parts of Disko (grønArctic Energy Inc., 1996).

Following on their reconnaissance magneto-telluric survey in 1995, grønArctic has also planned further geologi-

Table 3. Technical data from the grønArctic well GANK #1

Well name:	grønArctic Nuussuaq Kuussuaq #1 (GANK #1)
Operator:	grønArctic Energy Inc., Calgary, Alberta, Canada
Drill contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada
Locality:	Aaffarssuaq valley, Nuussuaq, West Greenland
Co-ordinates:	70°28′25″ N, 53°53′25″ W
Elevation:	91 m a.s.l.
Well spud date:	11 August 1995
Termination:	28 August 1995
Rig type:	Longyear 44 diamond core drill, adapted mining rig
Total depth:	398 m , ~100% core recovery
Hole diameter:	0–168 m: 96.0 mm (HQ rods),
	168–398 m: 75.8 mm (NQ rods)
Core diameter:	0–168 m: 63.5 mm,
	168–398 m: 47.6 mm
Status:	Plugged and abandoned
Main target:	Structural Marraat-type prospect (oil generated from Tertiary deltaic source rock, Tertiary or Cretaceous sandstone reservoir)
Formations drilled:	Lower Tertiary volcanics (115 m), Lower Tertiary and ?Cretaceous clastic sediments (273 m)
Hydrocarbons:	Traces of oil in volcanics and sediments, some gas under pressure in sandstones

Fig. 4. Flaring gas at GANE #1 in the Aaffarsuaq valley, Nuussuaq.

cal and geophysical activities in 1996. The new activities are planned to include airborne magnetics and gravimetrics, a magneto-telluric survey, satellite imagery, microbial prospecting and slim hole drilling (grønArctic Energy Inc., 1996).

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The drilling of stratigraphic borehole Umiivik-1, Svartenhuk Halvø, West Greenland

Kevin J. Bate and Flemming G. Christiansen

Svartenhuk Halvø is one of the few areas onshore West Greenland where Upper Cretaceous and Lower Tertiary marine sediments are exposed (Fig. 1). Geological studies in the area have been made intermittently since the late 1930s but have intensified since 1990 as part of the Survey's overall effort to assess the petroleum potential of the Disko – Nuussuaq – Svartenhuk Halvø area and adjacent offshore basins. The search for evidence that a marine oil source rock of Cenomanian – Turonian age exists in West Greenland has been a preoccupation of the Survey since 1992 when it was first predicted that this was the most likely level for an oil source rock in the region (Chalmers *et al.*, 1993). Oil-prone source rocks exist (in other locations) world-wide within the Cenomanian – Turonian succession associated with a global sea-level highstand. Recently, marine mudstones of this age with TOC (Total Organic Carbon) values of typically 8% or more and Hydrogen Indices of 300 to 500 have been described from the Sverdrup Basin on Ellesmere Island in the Canadian Arctic (Núñez-Betelu, 1993). If a similar source rock could be proved to exist in West Greenland it would be the first documented occurrence of an oil-prone source rock of this age in the region and would enhance the prospectivity of both offshore southern West Greenland and Melville Bay to the north.

In order to test this possibility the Government of Greenland and the Danish State provided funding for the drilling of the Umiivik-1 borehole on Svartenhuk Halvø where the oldest known Cretaceous marine sediments in West Greenland are exposed at surface. These comprise mudstones of Coniacian – Santonian age deposited in relatively deep water environments suggesting good possiblities to penetrate the Cenomanian – Turonian succession and to intersect a marine oil-prone source rock.

Setting and stratigraphy

The West Greenland margin is a rifted continental margin, developed during the opening of the Labrador Sea in the late Mesozoic – early Cenozoic (Chalmers *et al.*, 1993). In response to this break-up a number of rift basins developed along this margin in which a succession of early Cretaceous – Tertiary sediments were deposited (Pedersen & Pulvertaft, 1992; Dam & Sønderholm, 1994). Onshore exposures of these sediments extend from Svartenhuk Halvø south to Disko (Fig. 1). The outcrops are bounded to the east by a faulted contact with basement which consists of Precambrian gneisses and metasediments (Rosenkrantz & Pulvertaft, 1969; Pedersen & Pulvertaft, 1992). The sediments are overlain by Paleocene flood basalts.

Field mapping has identified a NW–SE structural trend in the Svartenhuk Halvø area (Larsen & Grocott, 1991). On the south-eastern coast of the Umiivik bay the marine Cretaceous sediments dip gently to the south-west but the dip swings slightly to a more westerly direction around Firefjeld. The sediments exposed at surface are predominantly dark grey to black mudstones which are likely to have been deposited in an outer shelf to slope environment. A number of dolerite intrusions can be identified cutting through these sediments in cliff sections.

Recent exploration history

In 1992 the Geological Survey of Greenland (GGU) drilled five holes on eastern Svartenhuk Halvø as part of a systematic shallow coring project in the Disko – Nuussuaq – Svartenhuk Halvø area (Christiansen, 1993), forming the basis for renewed sedimentological, palynological and organic geochemical studies (Christiansen *et al.*, 1994). The drilling programme was undertaken using a helicopter-portable wire-line rig. Total depths of these holes ranged between 66 m and 86 m.

Prior to the drilling of Umiivik-1, the deepest borehole in the area was GGU shallow borehole 400709 which reached a total depth of 86.24 m and is situated 15.5 km to the north-north-west. This borehole intersected the oldest sediments known at that time in the Svartenhuk Halvø area, of Coniacian to Early Santonian age (Nøhr-Hansen, 1994, in press).

During the 1994 field season a seismic programme involving the acquisition of a single refraction and reflection line was carried out along the southern shoreline of Umiivik in collaboration with the seismic consultant Rambøll, Hannemann & Højlund A/S (Christiansen *et al.*, 1995). A total of 11.5 km of seismic data was acquired. The seismic line was placed where Santonian marine black mudstones

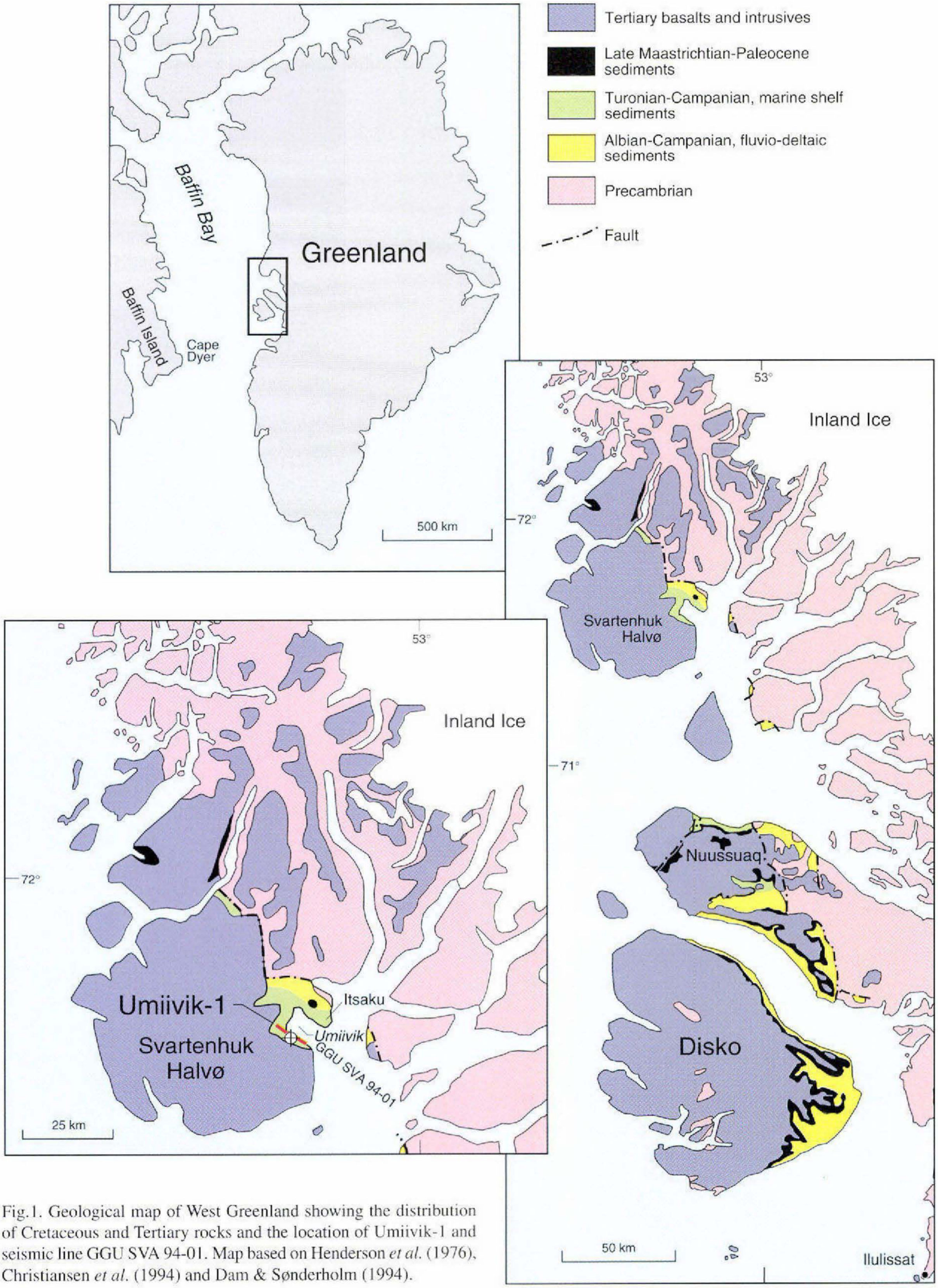

Fig. 1. Geological map of West Greenland showing the distribution of Cretaceous and Tertiary rocks and the location of Umiivik-1 and seismic line GGU SVA 94-01. Map based on Henderson *et al.* (1976), Christiansen *et al.* (1994) and Dam & Sønderholm (1994).

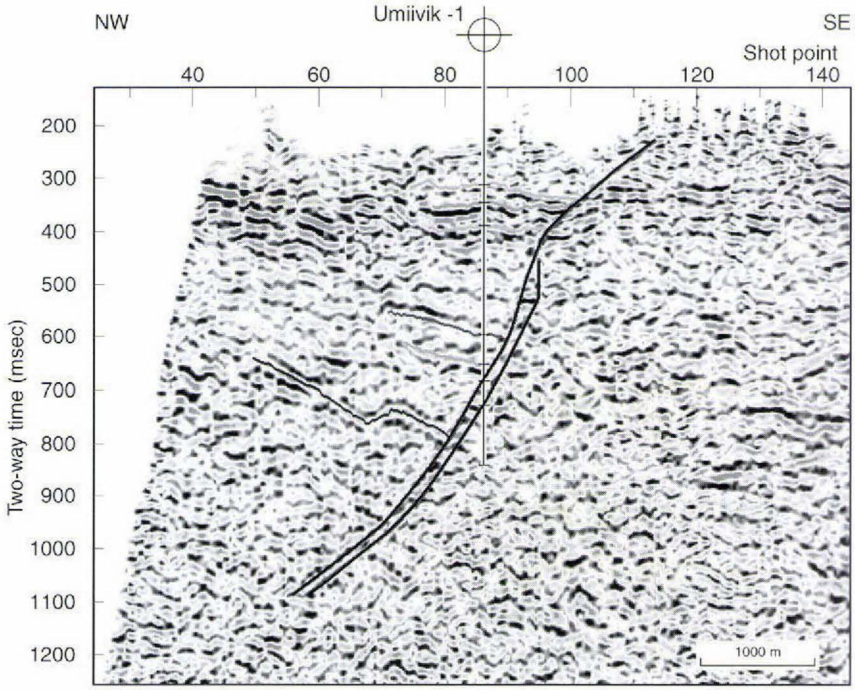

Fig. 2. Part of seismic line GGU SVA94-01 showing interpretation based on drilling results. Solid lines: assumed north-north-west dipping faults.

outcrop along the coast. The results of the final processing and initial interpretation did not allow a confident estimate as to the Two Way Time (TWT) to the base of the sedimentary succession; however, it did indicate a weak synclinal attitude to the subsurface geology (Fig. 2). A strong, fairly continuous reflection was seen extending across the entire section between 250 to 400 msec TWT which was interpreted as representing the base of the marine mudstones. The section below this reflector was interpreted as either early Cretaceous fluviatile sandstones similar to those exposed on the north-east side of the Itsaku peninsula 15 km to the north, or Precambrian basement (Fig. 1). However, the presence of reflectors to a TWT ranging between 800 to 1400 msec makes the latter proposal unlikely. A number of prominent reflectors on the south-eastern end of the line were interpreted to represent Tertiary intrusions, and a diffraction pattern with an origin at shot point (SP) 109 was interpreted to indicate a major fault down throwing to the north-west (Fig. 2).

Drilling of Umiivik-1

Well Umiivik-1 was drilled by grønArctic Energy Inc. of Calgary, Alberta, Canada as part of a turnkey contract entered into between the Government of Greenland, Minerals Office (Operator) and grønArctic Energy Inc., with the Geological Survey of Denmark and Greenland (GEUS) providing the geological services (see Table 1). The drilling services were provided by Petro Drilling Ltd.

Table 1. Pertinent well data for Umiivik-1

Well name:	Umiivik-1
Operator:	Government of Greenland, Minerals Office turnkey contract with grønArctic Energy Inc., Calgary, Alberta, Canada
Drilling contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada
Locality:	Svartenhuk Halvø, West Greenland
Co-ordinates:	71°36′42″N, 54°02′31″W
Elevation:	~ 5 m a. s. l.
Well spud date:	21 August 1995
Termination:	13 September 1995
Rig released:	15 September 1995
Total Depth:	1200 m, ~ 100% recovery
Rig type:	Longyear fly-in 50 diamond core drill, adapted mining rig
Hole diameter:	0–148 m: 96.0 mm (HQ rods), 148–1200 m: 75.8 mm (NQ rods)
Core diameter:	0–148 m: 63.5 mm, 148–1200 m: 47.6 mm
Status:	Plugged and abandoned
Main target:	Stratigraphic well with the main aim to demonstrate a Cenomanian – Turonian marine source rock for oil
Formation drilled:	Upper Cretaceous marine mudstones (1200 m) with occasional Tertiary intrusions
Hydrocarbons:	Gas bleeding from core within mudstone sections

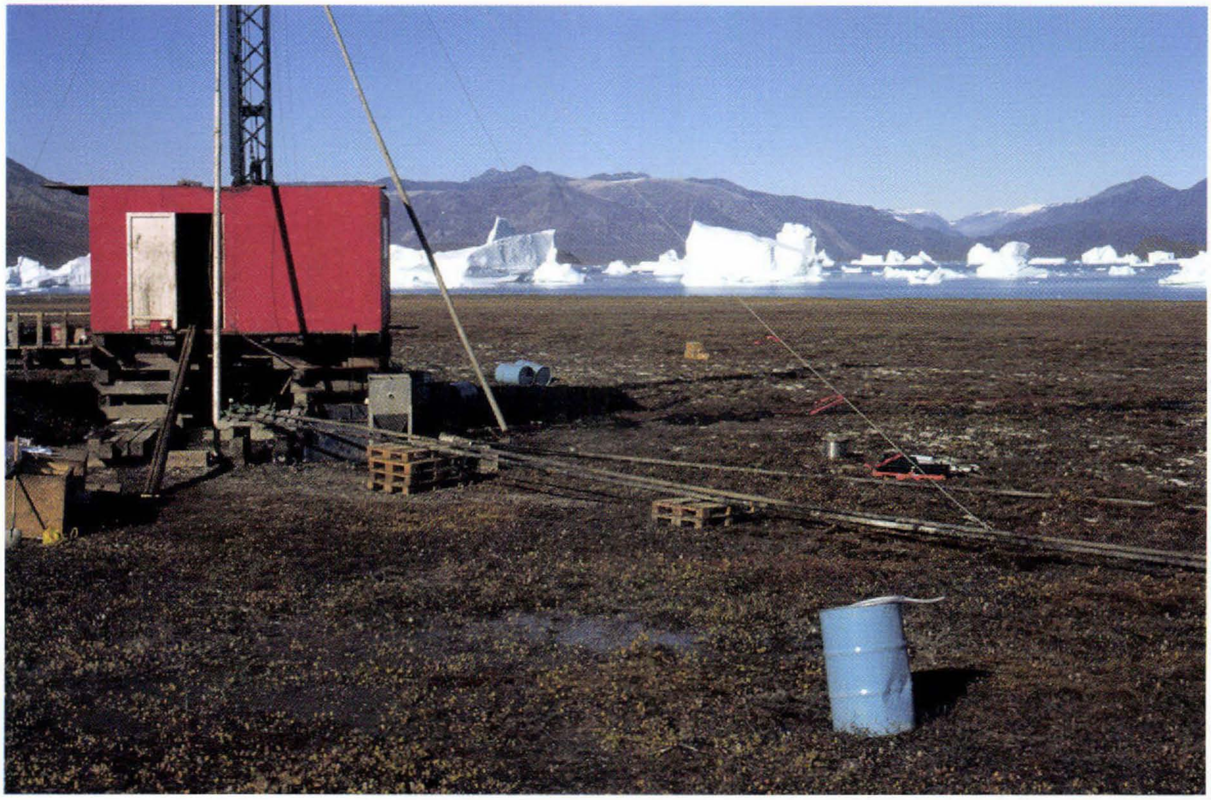

Fig. 3. View of the Longyear wire-line drilling rig at the Umiivik-1 well-site on Svartenhuk Halvø.

of Halifax, Nova Scotia, Canada, using a modified Longyear wire-line drilling rig (Fig. 3; Table 1). The borehole was spudded on 21 August and was terminated at the contract depth of 1200 m on 13 September, 1995. GEUS was responsible for the well-site geological services which included the preliminary geological description of the core and collection of samples (Bate, 1996). This was followed by detailed analysis in Copenhagen of all samples of core, fluids and gases collected at the wellsite, together with storage of all material taken.

The location of the Umiivik-1 borehole is on the southern coast of Umiivik (Fig. 1) at approximately shot point 86 on seismic line GGU SVA94-01 (Fig. 2). This position facilitated the drilling of a thick sedimentary succession prior to intersection of the presumed large fault interpreted on the seismic data. Further constraints on the positioning of the rig included availability of sufficient water supply, adequate containment facilities and ease of crew changes.

A total of 1200 m of core was recovered from Umiivik-1 (Fig. 4) with recovery close to 100%. Almost the entire core consists of dark grey, firm and non-calcareous mudstone with abundant silty interbeds. This general lithology was maintained until the contract termination depth (TD) was reached at 1200 m. Such a thick accumulation of mudstone was unexpected and it will require a significant re-evaluation of basin development in the Svartenhuk Halvø area. Based on the preliminary interpretation of the seismic data it had been expected that the well would intersect either non-marine sandstones or basement below a depth of approximately 800 m. The position of the base of the mudstone section now remains conjectural as no obvious basement reflector is evident on the seismic data below the total depth of the hole. A total of nineteen large dolerite intrusions were intersected throughout the well with a cumulative thickness of 238.25 m. These intrusions have raised the local thermal maturity of the mudstones to such a level that little generative potential remains. Similar degradational thermal effects of intrusions on the generative potential of mudstones in the Svartenhuk Halvø area have been documented by Schiener & Perregaard (1981). One such intrusion over the depth interval 952 m to 1027 m is highly fractured, and resulted in slow penetration and poor core recovery. This heavily fractured intrusion is interpreted as the presumed large fault imaged on the seismic data.

Indications of hydrocarbons were initially encountered at a depth of 245 m (Fig. 4). Gas escaping from the core was audible (bursting against the aluminium foil in which the core was wrapped). The frequency and rate at which gas was escaping from the core increased with depth and over certain intervals formed a white froth on the surface

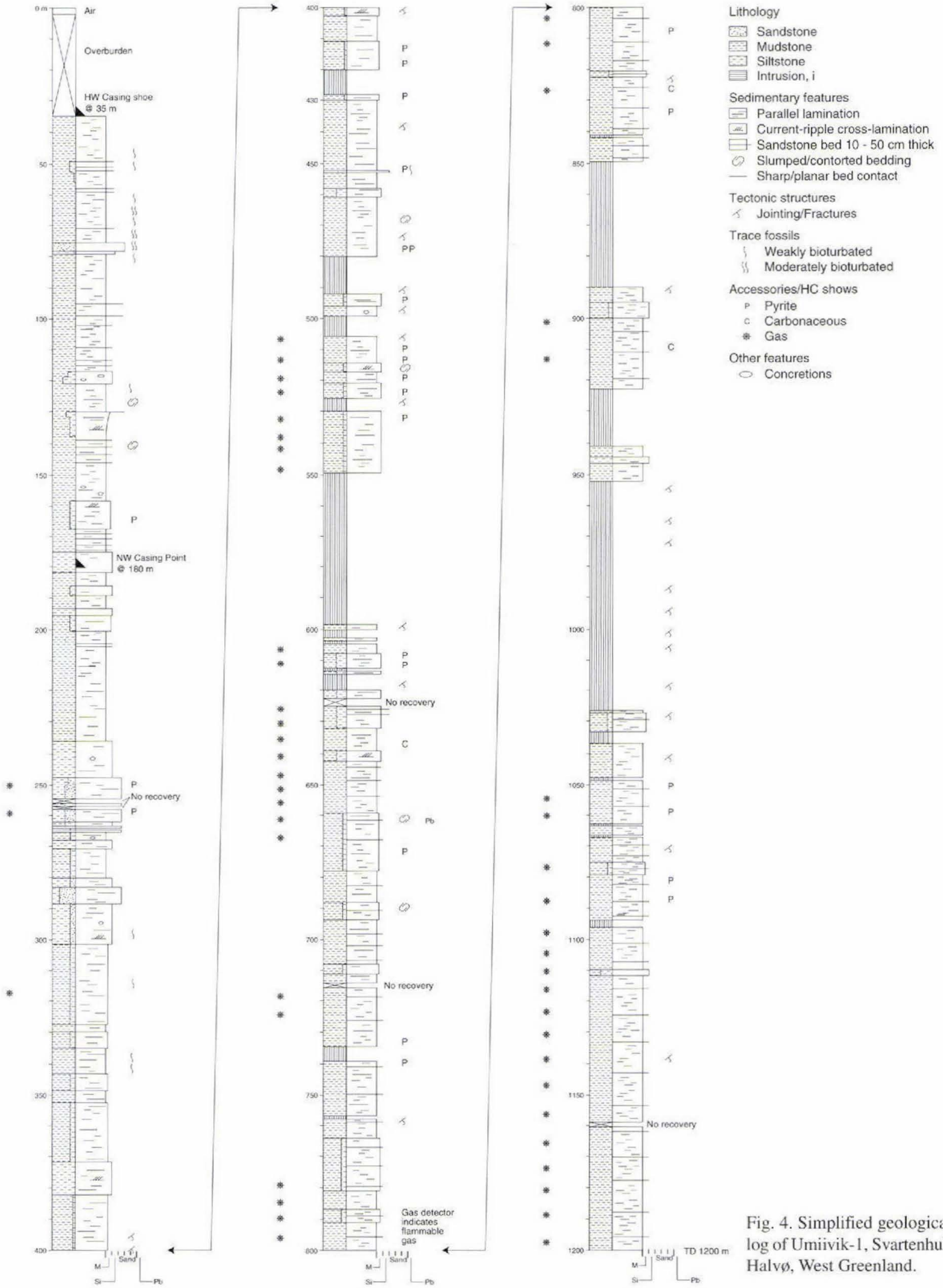

Fig. 4. Simplified geological log of Umiivik-1, Svartenhuk Halvø, West Greenland.

of the core as soon as it was removed from the core barrel. Indications of gas persisted throughout the mudstone sections of the hole, with only the intrusive sections not exhibiting any indications of gas.

The preliminary organic geochemical results show moderate to high (2.5–6.5%) values of TOC (Total Organic Carbon) throughout the mudstone section. In the uppermost 390 m of the core in which the sediments are immature (T_{max} below 438°C, R_o below 0.63%), the Hydrogen Index values are typically between 75 and 125 suggesting only a minor, if any, potential for oil, but a significant gas potential. In the deeper part of the core, from 405 m to 1200 m, in which the sediments are post mature (T_{max} above 500°C, R_o above 2.0%) Hydrogen Index values are below 35, in many cases below 5, and it is not possible to interpret the original generative potential prior to heating by the intrusions.

Head space analyses from tin cans containing the core samples often show very high gas concentrations (more than 50% hydrocarbons). Most of the gas is relatively dry (mainly methane), but below 750 m, most samples indicate a rather wet gas with high concentrations of ethane and propane and significant amounts of butane and pentane. These data suggest that this mudstone succession, prior to heating from the intrusions, also had a significant generative potential for condensate, perhaps also for oil.

In summary it can be concluded that the results of the drilling of Umiivik-1 have demonstrated a much greater thickness of mudstone than was predicted from the seismic data. In general the organic richness of the mudstones is moderate to high but the sediments have been thermally degraded by intrusions to such an extent that they are post-mature for oil generation. A well drilled through similar mudstones but without intersecting any large intrusions might produce more encouraging results as to the prospectivity of the Svartenhuk Halvø area.

Acknowledgements. Funding for the drilling project was provided from the Government of Greenland, Minerals Office and the Danish State through the Mineral Resources Administration for Greenland. The drilling programme was completed in collaboration with two Canadian companies: grønArctic Energy Inc. and Petro Drilling Ltd. Greenland Air provided helicopter support for the duration of the project and Dykkerselskabet provided the support vessel *Viking Naja*. In particular thanks are due to Cam Hanna of grønArctic Energy Inc. for good planning and technical support.

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A preliminary seismic interpretation of an area with extensive Tertiary basalts offshore central West Greenland

Richard C. Whittaker

A seismic and geological interpretation of the area between latitudes 67°30′N and 73°N offshore West Greenland, was completed in 1995 and has been published as an Open File Series report (Whittaker, 1995). The area is characterised by extensive Early Tertiary basalts which are the seaward extension of the plateau basalts exposed in the Disko – Nuussuaq – Svartenhuk Halvø area onshore (Clarke & Pedersen, 1976). These basalts present special problems in the processing and interpretation of seismic data. The interpretation incorporates all the seismic data acquired prior to the 1995 field season, including those lines acquired during the first phase of exploration in the 1970s. Ties to two of the exploration wells drilled offshore southern West Greenland have led to a greater understanding of the timing and kinematics of tectonic events during the Tertiary period; such events are not recorded in the onshore area. The area is considered to have significant exploration potential and warrants additional studies to determine the thickness of the basalt formation in the area.

Background

This interpretation completes the final stage of a major seismic project involving the interpretation of all the newer seismic data in West Greenland from the Melville Bay area in the north (Whittaker & Hamann, 1995) to the entire continental shelf of southern West Greenland in the south (Chalmers *et al.*, 1995).

The area covered in this study extends approximately 600 km from latitudes 67°30′N to 73°N and 200 km from east to west (Fig. 1). This large underexplored region is important to regional geological understanding and to petroleum exploration in West Greenland as a whole. Seismic data in the area provide a means of correlating geological data from the five offshore oil exploration wells in southern West Greenland with the Melville Bay area which is believed to have outstanding exploration potential. Information gained from this study will also be useful in the assessment of the adjacent Disko – Nuussuaq – Svartenhuk Halvø area where a commercial exploration programme has begun. The discovery onshore of oil shows in basalts on Nuussuaq (Christiansen *et al.*, 1996) has also upgraded the potential for an offshore sub-basalt oil play.

Water depths over most of the continental shelf in the area described are between 100 m and 500 m, with a significant proportion shallower than 200 m. Physical conditions in the area are, however, harsh. The sea freezes over in November, and the sea-ice does not break up until June (Thomsen, 1993). Scattered large icebergs derived from glaciers draining the Greenland Inland Ice are present throughout the year. However, experience has shown that geophysical surveys can be carried out in the summer field season with very little down-time, and offshore oil exploration wells were drilled farther south as long ago as 1976.

Seismic interpretation

The seismic data interpreted during this study vary considerably in quality and resolution. Approximately 2500 km of modern multifold reflection seismic data were acquired in the area during surveys carried out in 1990 and 1992. In addition there are 4000 km of older seismic data, acquired by the oil industry during the first phase of oil exploration in the 1970s; these are generally of poor quality but are still useful in defining structural trends and in mapping horizons.

A total of eight horizons were picked on the seismic lines and depth converted using the ECHO mapping system. These horizons were then contoured to produce a series of structural maps and the probable geological age of these horizons has been assessed. The structure contour map of the top of the Tertiary volcanics horizon is shown in Fig. 1. In general, age determination becomes less reliable farther north in the area, away from the well control, and horizons beneath the top of the Tertiary volcanics are of a more speculative nature.

Before the start of the study it was assumed that it was not possible to see reflectors beneath the thick Tertiary volcanic section. Closer inspection of the data, however, has shown that it is possible to interpret horizons deeper than the top of the volcanics, and a thick Cretaceous sedimentary section is inferred to be present.

Cretaceous sediments encountered in the Ikermiut-1 well can be tied directly into the south-east corner of the area where the Tertiary basalts are absent. The eastern end of seismic line GGU/90-4 (Figs 1, 2) has a section about

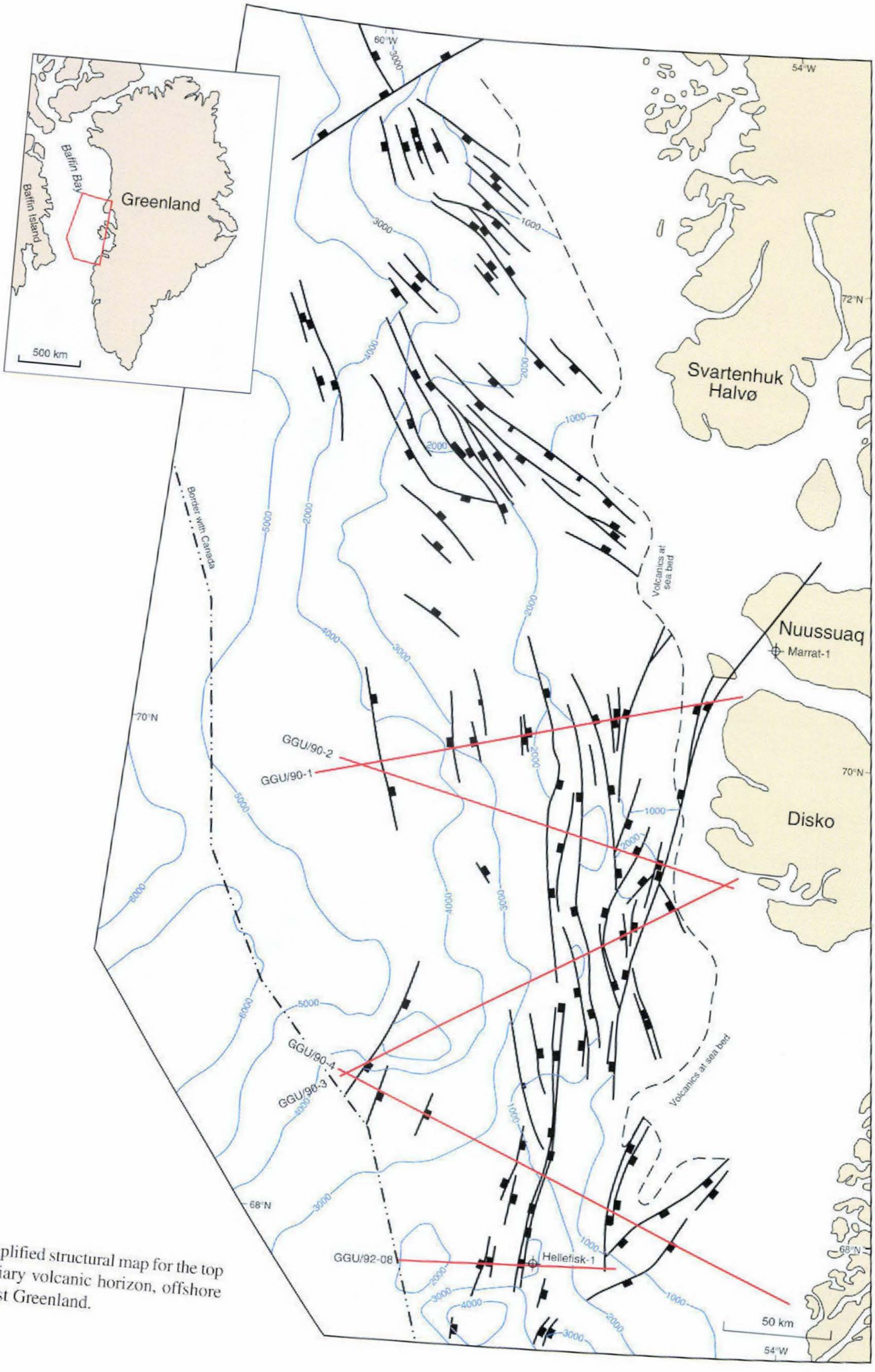

Fig. 1. Simplified structural map for the top of the Tertiary volcanic horizon, offshore central West Greenland.

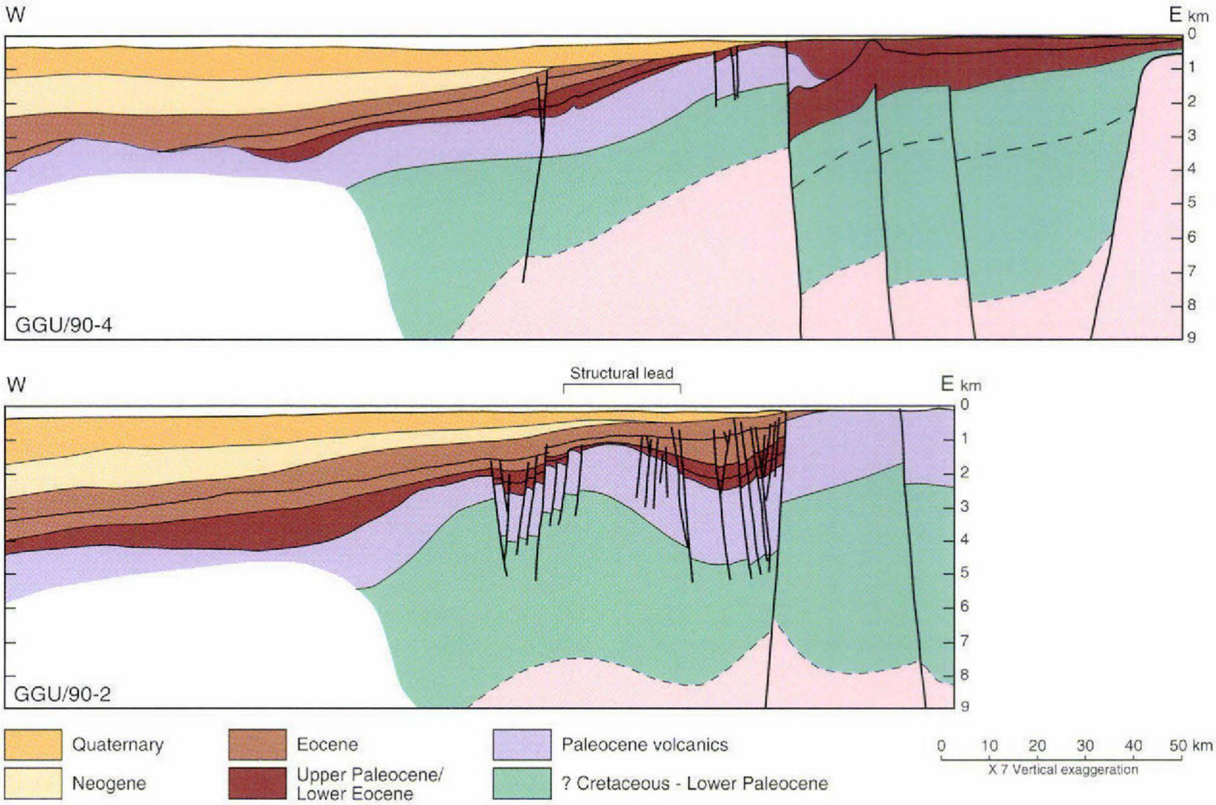

Fig. 2. Cross-sections drawn from depth-converted seismic lines GGU/90-2 and GGU/90-4, central West Greenland. Location of cross-sections shown on Fig. 1.

6000 m thick below the base of the Tertiary. Seismic lines to the west of Disko (line GGU/90-2, Figs 1, 2) also show the presence of deep reflectors which are interpreted as Cretaceous sediments up to 5000 m thick. Internal reflectors can clearly be seen within the volcanic interval and in several places dipping reflectors can be seen to subcrop at the top of the Tertiary volcanics horizon. This truncation of the top of the basalts indicates that substantial erosion of the volcanic interval took place during the Early Tertiary.

Upper Paleocene and younger sediments can be tied to the Hellefisk-1 well, drilled in the southern part of the area. Post-volcanic sediments occur throughout the area, except where basalts outcrop at the sea bed (Fig. 1). The basal part of the Eocene section onlaps topographic highs, and thickness changes within this interval indicate that sedimentation at this time was controlled by structure and the southern limit of the basalts.

A second major regional unconformity can be seen at the base of the Neogene section. The overlying sediments onlap towards the east, and gradually thicken towards Baffin Bay, reaching a maximum thickness of 2000 m in the west. The overlying Pliocene – Quaternary interval is a prograding sedimentary wedge which, in the south-eastern part of the area, was deposited in deep channels or canyons.

Tectonic implications

Thick Cretaceous rift deposits are interpreted to be present in the area but poor seismic resolution in this interval, caused by the overlying thick Tertiary volcanic section, results in a lack of detailed information about this phase in the development of the basin. An early extensional period is known to have affected other nearby areas (Chalmers *et al.*, 1995). The Tertiary tectonic development can, however, be resolved with more clarity.

The northern and southern margins of the offshore basalts are controlled by NE–SW trending faults; this is also the direction of opening of the Labrador Sea during the extrusion of the basalts. Shale diapirs and shale-cored folds trending NW–SE are seen immediately north and south of the basalts.

Compressional structures, also seen in the Melville Bay area (Whittaker *et al.*, submitted), are confirmed to have developed towards the end of a period of extension in the Paleocene (Fig. 2). These structures are believed to have resulted from transpression in a major transform zone, the Ungava Fracture Zone, which links the Baffin Bay oceanic basin to the Labrador Sea in the south. The structures formed in the Late Paleocene – Early Eocene, at about the end of the first phase of sea floor spreading in the Labrador Sea, and continued to develop after the extrusion of the Early Tertiary plateau basalts. Sea floor spreading in Baffin Bay does not appear to have begun until after the period of basalt extrusion (Whittaker *et al.*, submitted).

The onset of sea floor spreading was followed by a relatively quiet period of thermal subsidence, with less active extensional faulting gradually dying out towards the end of the drift phase. The crests of anticlines formed during the phase of inversion were eroded in a period of Eocene syn-drift deposition, when transgressive marine sediments filled restricted basins in the irregular topography.

Steep faults penetrating the drift phase sediments are probably strike-slip faults related to the oblique spreading of Baffin Bay. The direction of sea floor spreading in Baffin Bay was roughly north–south, as was the second phase of spreading in the Labrador Sea. Strike-slip faulting continued to affect the region throughout the Eocene, with the formation of north–south transtensional grabens and NW–SE extensional faults.

Sea floor spreading is generally assumed to have continued until about the Oligocene–Eocene boundary (Srivastava, 1978); subsequently sedimentation took place by simple progradation into the Baffin Bay Basin. Seismic data from the study area indicate that there was a later period of subsidence, uplift and erosion. There is also evidence from the Labrador Sea and south-east Baffin Island that a high relief was established in the onshore areas during the Late Oligocene, and that uplift was renewed in the Late Miocene (Trettin, 1991). An indication of the minimum post-Paleocene uplift onshore West Greenland is provided by the occurrence of Early Paleocene marine mudstones at about 1000 m above sea level. The western part of the offshore area, however, does not appear to have been affected by this uplift and is now at the maximum depth of burial.

Petroleum potential

Several promising structural leads have been mapped at top volcanics level (Fig. 1), and cross-sections drawn from depth-converted seismic sections also illustrate the presence of large structural leads (Fig. 2). The most promising potential plays in the area are sub-basalt Cretaceous and Lower Paleocene plays which are also the primary objective outside the offshore basalt area. A possible secondary Tertiary objective identified above the basalts may also have a significant potential and could be present in other areas offshore West Greenland. The shallower potential reservoirs are anticipated to be Upper Paleocene – Lower Eocene shallow marine and delta-front sandstones similar to those encountered in wells in the Labrador Sea. A source for hydrocarbons could occur in the restricted basins which are interpreted to be present in the Paleocene.

The thick basalt section may yet prove an insurmountable obstacle to the prospectivity of the area, but this study is sufficiently encouraging to warrant continued exploration. Partly as a result of this study, additional seismic data were acquired in the area during the summer of 1995 (Christiansen *et al.*, this report).

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Resources of the sedimentary basins of North and East Greenland – an integrated petroleum and ore geological research project

Lars Stemmerik, Sven M. Jensen, John Korstgård, Hans K. Schønwandt, Finn Surlyk, Ole R. Clausen, Henrik Fougt, Karsten Kragh, Bjarne R. Langdahl and Jens Therkelsen

A multidisciplinary research project 'Resources of the sedimentary basins of North and East Greenland' was initiated in 1995 with financial support from the Danish Research Councils. This is a joint project involving the Geological Survey of Denmark and Greenland (GEUS), the Geological Institute of the University of Copenhagen, the Department of Earth Sciences of the University of Aarhus and the Danish Environmental Research Institute (DMU). The participants include staff members of the institutes, four Ph.D. students and three post-doctorate stipendiates. The project is divided into three parts that all relate to exploration and exploitation of minerals and hydrocarbons in the sedimentary basins of North and East Greenland (Fig. 1).

The purpose of the hydrocarbon related studies is to develop models for petroleum systems in the three different types of sedimentary basins outcropping along the margins of North and East Greenland; the three selected basins are of different age, tectonic style and lithology. Furthermore, these results will be used in studies of the sedimentary basins offshore East Greenland. It is hoped that key elements from the specific models can be extracted to formulate general models that will aid the basic understanding of petroleum systems of similar basins world-wide. The selected basins are: the Lower Palaeozoic Franklinian Basin of North Greenland, the Upper Palaeozoic to Tertiary strike-slip dominated Wandel Sea Basin of eastern North Greenland, and the series of Upper Palaeozoic to Tertiary rift basins of East Greenland (Fig. 1).

The objectives of the ore-related studies are to increase the knowledge of stratabound mineralisation processes by integrating textural analysis, fluid inclusion analysis and stable isotope studies with hydrocarbon-related research methods, including sedimentology, sequence stratigraphy and hydrocarbon geochemistry. The primary focus of research is the Citronen Fjord zinc deposit in the Franklinian Basin of North Greenland (Fig. 2), with the aim of establishing a model describing the lead isotope signatures of specific stratigraphical units and potential metal source rocks. The knowledge gained from these studies will subsequently be applied to the metal sulphide-bearing Upper Permian Ravnefjeld Formation of the East Greenland rift basins.

Environmental monitoring of mineral resources exploitation in the Arctic regions requires understanding of natural element dispersion mechanisms and patterns, and of the interrelationship between the biosphere and the rocks exposed to meteoric processes by any mining activity (see e.g. Steenfelt, this report). The role of biochemical cycles in stabilising or destabilising heavy metal sulphides in the meteoric environment will be studied in the Citronen Fjord area. This detailed study will be supplemented with biological baseline studies in order to identify areas that are environmentally sensitive to hydrocarbon and mineral exploration and exploitation.

During the 1995 field season, work was carried out in the Franklinian Basin of North Greenland and in the East Greenland rift basins. The investigations focused on ore geology and biochemistry in North Greenland and on structural geology, sedimentology and diagenesis in East Greenland. Additional fieldwork and studies of the petroleum systems in the Wandel Sea Basin of eastern North Greenland and the area around Kangerlussuaq in the southernmost of the East Greenland rift basins was carried out as part of investigations coordinated by GEUS and the Danish Lithosphere Centre, respectively (see Henriksen, this report; Larsen *et al.*, this report).

North Greenland

Ore geological and microbiological field work was carried out in two areas of North Greenland in 1995, supported logistically from the Survey base in eastern North Greenland (Henriksen, this report) and with additional helicopter support from Platinova A/S. A two-man team (later in the field season a three-man team) worked out of field camps in the Navarana Fjord area and the Citronen Fjord area (Fig. 1).

The regional studies focused on the numerous minor pyrite, galena and sphalerite occurrences that occur in a narrow belt of Cambrian-Ordovician outer shelf and slope sediments between the north coast of Nyeboe Land and Navarana Fjord (Figs 1, 2). The field relationships of the

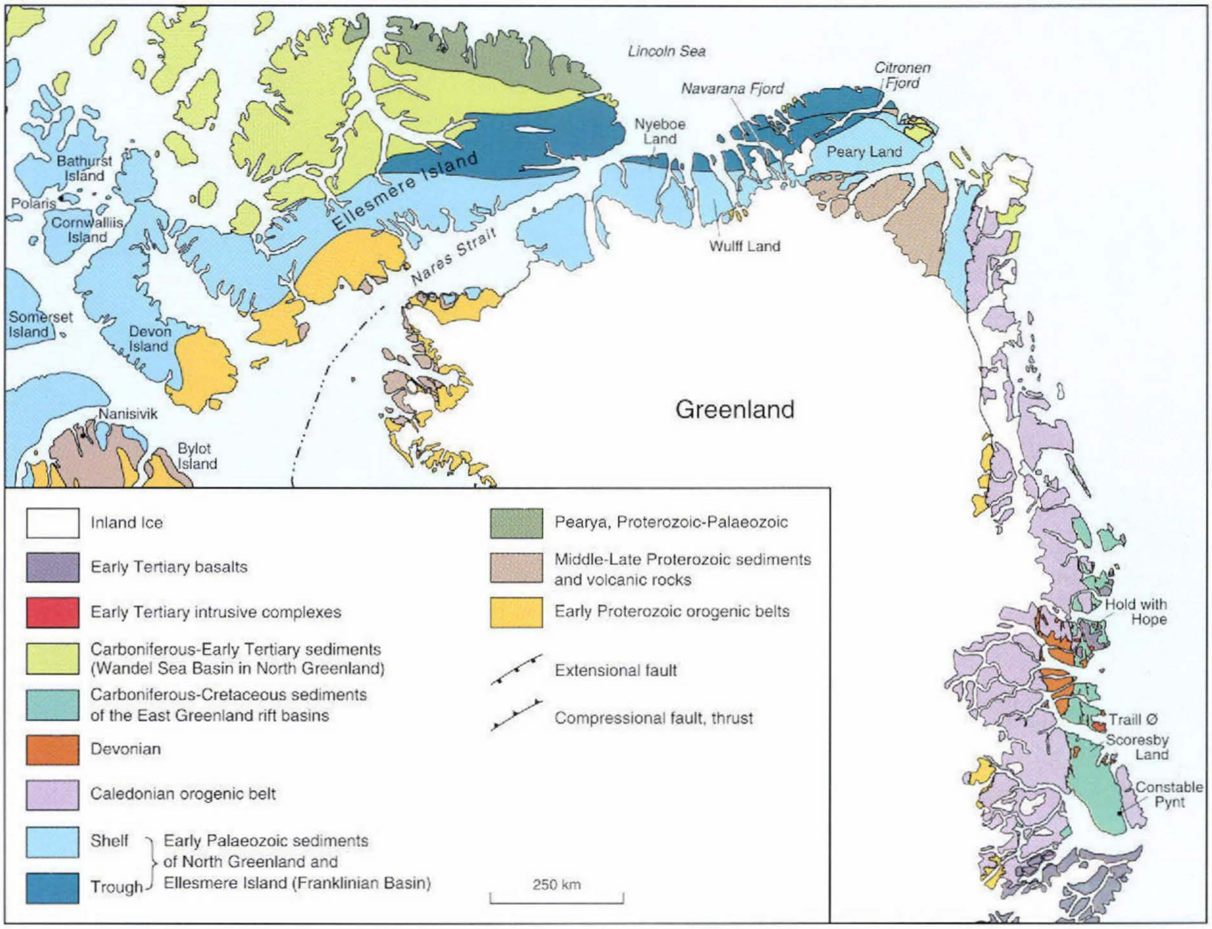

Fig. 1. Geological map of northern and eastern Greenland and eastern Canada showing outline of investigated basins.

sulphide mineralisations were investigated and collections made for ore petrographic studies, lead and stable (primary sulphur) isotopic analyses and fluid inclusion studies.

The Citronen Fjord zinc deposit is by far the largest mineral occurrence known in North Greenland. It is a stratiform, shale-hosted sedimentary exhalative (SEDEX) deposit within shales and cherts of the Upper Ordovician – Lower Silurian Amundsen Land Group (Higgins *et al.*, 1991). The host sediments were deposited on a sediment-starved continental slope separated from a wide carbonate platform to the south by the prominent Navarana Fjord escarpment. The ore-bearing sediments are laminated mudstones interbedded with turbiditic sandstones and two major carbonate debris flow units of the Citronens Fjord Member (Hurst & Surlyk, 1982). The ore has a simple mineralogy that includes pyrite, carbonates, sphalerite and galena. Spectacular primary and diagenetic textures are well preserved within the deposit. The primary textures are comparable with textures found in recently precipitated sulphide mounds on the seafloor, e.g. the Juan de Fuca Ridge in the Pacific Ocean (Paradis *et al.*, 1988). Preliminary data from the Citronen Fjord deposit indicate that the mineralised zones form discrete mounds composed of semi-massive to massive sulphide and carbonate intergrowths. The general textural element comprises different types of sulphide spheres including framboids, radiating spheres with complex intergrowths of pyrite, sphalerite, galena and carbonate, and massive spheres with small spheroidal inclusions of carbonate. Well-laminated sulphides interbedded with mudstone occur on the flanks of the sulphide mounds. The sulphide laminae consist of framboidal pyrite with interstitial carbonate and sphalerite (Fig. 3). In places secondary pyrite has overgrown the framboids, and later carbonates have partly replaced the pyrite. A description and interpretation of these textures form the main contribution to this part of the project.

A newly developed numerical, lithogeochemical methodology for recognition and quantification of alterations associated with hydrothermal mineralisations has been tested on a variety of large sediment-hosted massive sul-

Fig. 2. Zinc-mineralised carbonate debris flow, top of Aftenstjernesø Formation, eastern Navarana Fjord. In the field, minor amounts of sphalerite can be detected indirectly by the presence of oxidation products (red-stained in insert photo).

phide deposits by C. R. Stanley, Mineral Deposit Research Unit (MDRU), University of British Columbia. The lithogeochemical approach will be tested on the Citronen Fjord deposit, in collaboration with MDRU, using samples collected in 1995. The methodology employs a combination of molar ratio diagrams, linear algebra and X-ray diffraction to constrain a 'background' model for the compositional variability of the unaltered sedimentary succession. Deviations from this model then indicate the nature and degree of hydrothermal alteration.

Microbiological studies

In order to test the role bacteria might play in forming the giant gossans developed on the massive sulphides outcropping in the Citronen Fjord area (see Schønwandt, 1994) surface material and water from streams draining the gossans were collected and analysed at the Department of Microbial Ecology, University of Aarhus. Provisional results show the presence of sulphide-oxidising bacteria and a previously undescribed acid-tolerant yeast strain (Langdahl, 1995). These results encourage further studies of the microorganisms and the microbial sulphide oxidation processes that form the very low-pH drainage below the gossans. The 'natural heavy metal pollution' in the Citronen Fjord area will be an important reference standard for future investigations concerning the effect of mining activities on microbial processes in similar environments in the high Arctic.

East Greenland

In central East Greenland field work was carried out in central and eastern Traill Ø by two two-man teams supported by a helicopter based at Constable Pynt (Fig. 1). One team made structural studies of the post-Caledonian sediments, and the other studies of the Middle Jurassic sandstones. The area around Svinhufvud Bjerge is dominated by Lower Triassic reddish-grey sandstones and shales, Middle Jurassic yellowish sandstones, and dark grey Lower Cretaceous shales. An erosional remnant of Upper Jurassic shales of the Bernbjerg Formation conformably overlies the Middle Jurassic sandstones in the eastern part of Svinhufvud Bjerge. The Jurassic – Cretaceous boundary is an erosional and angular unconformity (Fig. 4). All sediments are intruded by early Tertiary basic sills and dykes, which often control the present topography.

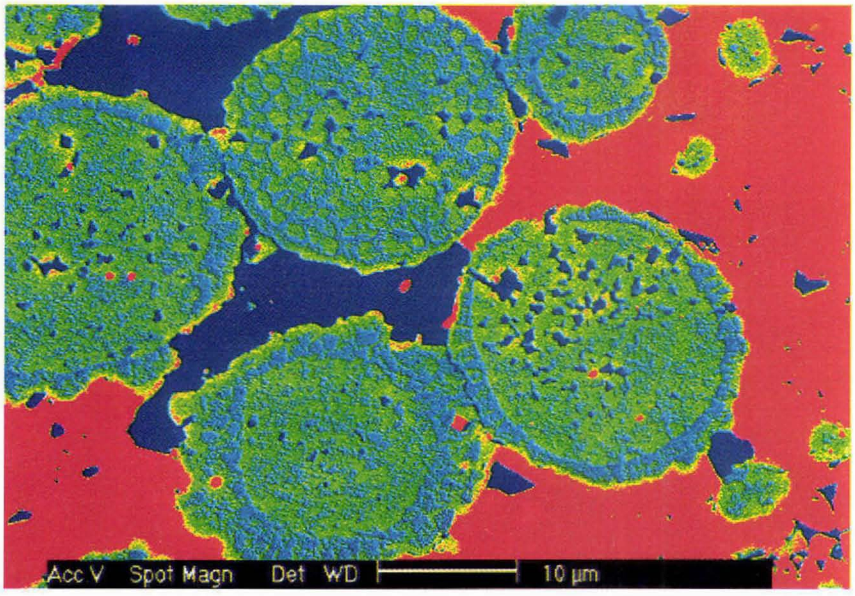

Fig. 3. False-colour scanning electron microscopy image showing pyrite framboids with secondary pyrite overgrowths. Green is pyrite, red is sphalerite and blue is carbonate gangue minerals.

The Middle Jurassic sandstones have a maximum thickness in excess of 650 m on eastern Traill Ø. The lower part of the succession is dominated by coarse-grained fluvial sandstones and conglomerates with thin coal seams and minor intervals of shales in which well developed root horizons occur. The upper part of the succession is generally more fine-grained and contains marine trace fossils and rare ammonites.

The Svinhufvud Bjerge region is cut by N–S striking, eastwards dipping major faults which define a complex pattern of fault blocks. These fault blocks are cut by ENE–WSW trending accommodation faults, and minor antithetic and synthetic faults. The major faults are characterised by an orange fault breccia; fragments of all rock types in the area, including the basic dykes, are present in the breccia embedded in a reddish matrix. This breccia preserves evidence for several slip events. The accommodation faults do not have any associated breccia, but exhibit a complex geometry of small fault blocks with well defined fault planes and drag folds. The minor synthetic and antithetic faults downthrow the Upper Jurassic Bernbjerg Formation with respect to the top of the Middle Jurassic sandstones, such that the Bernbjerg Formation is preserved below the basal Cretaceous unconformity. The minor faults are thus important for a structural understanding of the area and also appear to control the present location of sediments.

Lateral sedimentary changes and structural observations in Svinhufvud Bjerge show that the N–S trending faults have controlled basin evolution since at least mid-Jurassic times. This is shown by: (1) deposition of the Middle Jurassic sandstones that can be linked to movements on faults; (2) the downthrown Bernbjerg Formation which indicates that faulting along major faults and associated antithetic faults took place either during deposition of the Bernbjerg Formation or during uplift associated with the development of the basal Cretaceous unconformity; (3) the geometry of conglomeratic debris flow deposits within the Lower Cretaceous shales on the central fault block which indicates that minor movements took place along the major faults throughout the Early Cretaceous; (4) the character of the fault breccia which shows that the major faults suffered significant offset after intrusion of the Tertiary basic sills and dykes.

Future work

Material collected during the 1995 and earlier Survey expeditions to North Greenland will be compared with sample material from the Nanisivik and Polaris mineral deposits in Arctic Canada. Ore petrographic studies will be supplemented by lead isotope analyses at the Institute für Geowissenschaften und Lithosphärenforschung, Justus-Liebig-Universität, Giessen, Germany. Sulphur isotope analytic work will be carried out at the Scottish Universities Research and Reactor Centre in Glasgow. Preliminary results from Peary Land show a very wide range of lead isotope signatures for galena samples, suggesting a variety of source rocks for the metals. The source of the sulphur and the temperature of the fluids from which sphalerite was precipitated will be determined by sulphur isotopic analyses, supplemented by fluid inclusion studies where applicable.

Field investigations will continue in both North and East Greenland in summer 1996. In North Greenland ore-geological studies will be continued in central and eastern Peary Land and around Citronen Fjord, and a more detailed

Fig. 4. Basal Cretaceous unconformity (BCU) seen from the west at Svinhufvud Bjerge, eastern Traill Ø. The southerly dipping Middle Jurassic sandstones are cut by the unconformity surface, which is overlain by Lower Cretaceous shales. Note post-Lower Cretaceous movements on the fault. The top of the mountain is a Tertiary sill complex.

combined ore-geological and sedimentological study will be carried out on Lower Palaeozoic platform carbonates in Wulff Land. Microbiological studies of the Citronen Fjord gossans will be continued.

In East Greenland field teams will study selected aspects of Upper Palaeozoic and Mesozoic geology in the region between northern Scoresby Land and Hold with Hope. The structural, sedimentological and diagenetic studies initiated in 1995 will be continued and supplemented by stratigraphic, sedimentological, diagenetic and ore-geological studies of primarily the Upper Permian, Triassic and Lower Cretaceous successions. The structural studies will be extended both north and south of Traill Ø, and older Carboniferous – Permian structures farther to the west will be included. The field based investigations will be supplemented by photogrammetric structural analyses on aerial photographs of central and eastern Traill Ø.

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Cretaceous – Tertiary pre-drift sediments of the Kangerlussuaq area, southern East Greenland

Michael Larsen, Lars Hamberg, Snorre Olaussen and Lars Stemmerik

The Cretaceous and Tertiary sedimentary succession around Kangerlussuaq in southern East Greenland is the least known part of the Upper Palaeozoic – Mesozoic rift basins exposed onshore East Greenland. The sediments were briefly described during initial mapping of the region (Wager, 1934, 1947; Wager & Deer, 1939), and later by Soper *et al.* (1976), Higgins & Soper (1981) and Nielsen *et al.* (1981). Detailed sedimentological studies of a few outcrops were carried out during the late 1980s (Hamberg, 1990; Nørgaard-Pedersen, 1991, 1992), but until now there have been no detailed sedimentological and stratigraphic studies of the region due to logistical difficulties; most of the outcrops are on isolated nunataks.

The main objects of the present study were to supplement the volcanic rifted margin investigations carried out by the Danish Lithosphere Centre (DLC) and to provide an insight into the basin development during Cretaceous to earliest Tertiary rifting. The pre-drift position of the Kangerlussuaq area close to present day petroleum exploration areas makes the sedimentary evolution a potential analogue model for the Cretaceous – earliest Tertiary sedimentary basins in the North Atlantic region (Fig. 1). These basins have acquired new interest as the focus of petroleum exploration has changed from the shallow shelf areas to deeper offshore areas like the Vøring, Møre and Faeroe-Shetland basins where thick successions of presumed Cretaceous – Tertiary age are preserved (e.g. Hinz *et al.*, 1993; Mitchell *et al.*, 1993).

The work during summer 1995 formed part of a major field campaign in the Kangerlussuaq area under the auspices of DLC (Fig. 2). The presence of two helicopters in the area allowed visits to hitherto undescribed sections and collection of data for sedimentological, stratigraphic and sequence stratigraphic analysis of the entire region has been achieved. The study forms part of a major research project on petroleum systems in the sedimentary basins of North and East Greenland supported by the Danish Research Councils (see Stemmerik *et al.*, this report).

Sedimentary evolution

Cretaceous and Early Tertiary clastic sediments in the Kangerlussuaq region overlie an irregular erosional surface of Precambrian crystalline basement that rises towards the west and north. They crop out below a several kilometre thick cover of Tertiary plateau basalts (Fig. 2), and are locally disturbed by Tertiary intrusions and major sill complexes. Most of the sediments were thus deposited before the onset of volcanism marking the beginning of sea-floor spreading in the Northern Atlantic close to the Paleocene – Eocene boundary at chron 24R. The sedimentary succession reaches *c.* 1 km in stratigraphic thickness and belongs to three formations: the Upper Cretaceous Sorgenfri Formation, the Upper Cretaceous – Paleocene Ryberg Formation of the Kangerdlugssuaq Group and the dominantly volcanic Paleocene – Eocene Vandfaldsdalen Formation of the Blosseville Group (Fig. 3) (Soper *et al.*, 1976).

During the 1995 field season a more than 150 m thick sandstone dominated succession of Early Cretaceous age was recorded below the Sorgenfri Formation. This succession records a change from fluvial and estuarine sandstones to deep marine shales probably related to the initial basin formation in the Late Aptian. The sandy succession

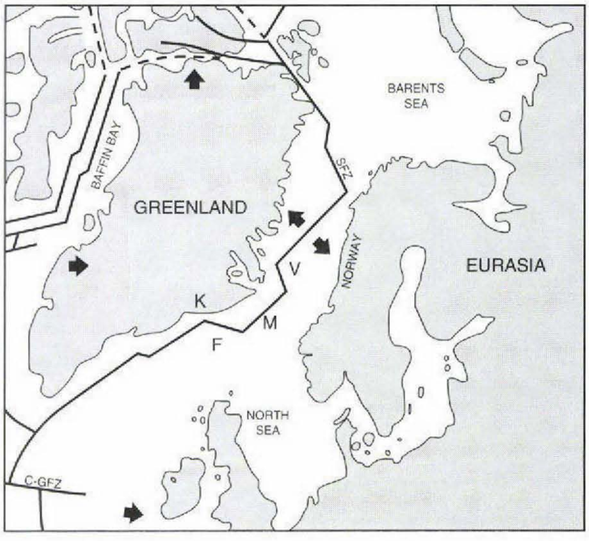

Fig. 1. Pre-drift palaeogeography of the Northern Atlantic showing the break-up during chron 24R near the Paleocene – Eocene boundary. K: Kangerlussuaq, F: Faeroe - Shetland Basin, M: Møre Basin, V: Vøring Basin. Modified from Myhre *et al.* (1992).

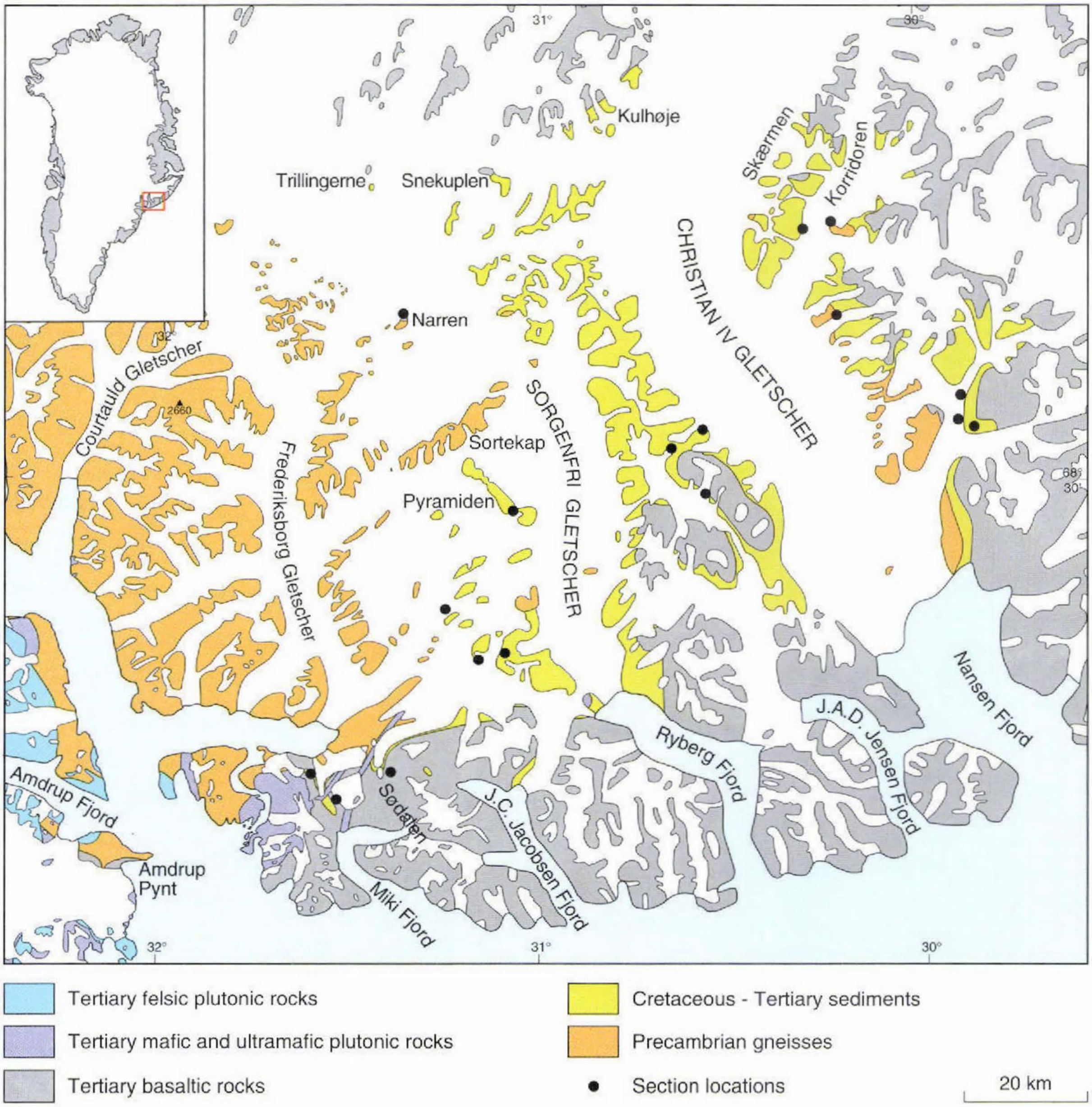

Fig. 2. Geological and location map of the Kangerlussuaq area showing the distribution of the pre-drift sediments. The positions of the main measured sections are indicated.

passes upwards into marine shales and thin turbidites of the Sorgenfri Formation.

The Upper Cretaceous Sorgenfri Formation was originally described from an isolated locality at Ryberg Fjord where it forms a 20 m thick succession of fossiliferous, grey laminated shale (Soper *et al.*, 1976). Later field work, however, has demonstrated a more extensive distribution and the formation is now believed to form a several hundred metres thick marine shale succession which is exposed at several localities inland e.g. at Pyramiden. The formation boundaries, however, remain ambiguous due to limited outcrops.

The Upper Cretaceous – Paleocene Ryberg Formation reaches *c.* 200 m in thickness and consists in the lower part of grey laminated siltstones and black shales alternating with thin turbidite beds of medium- to coarse-grained sandstones. A general coarsening-upward trend and increase in sandstone/mudstone ratio is recorded in the upper part of the measured sections, which show channelised sandstone units 20–35 m thick and separated by heterolithic shales.

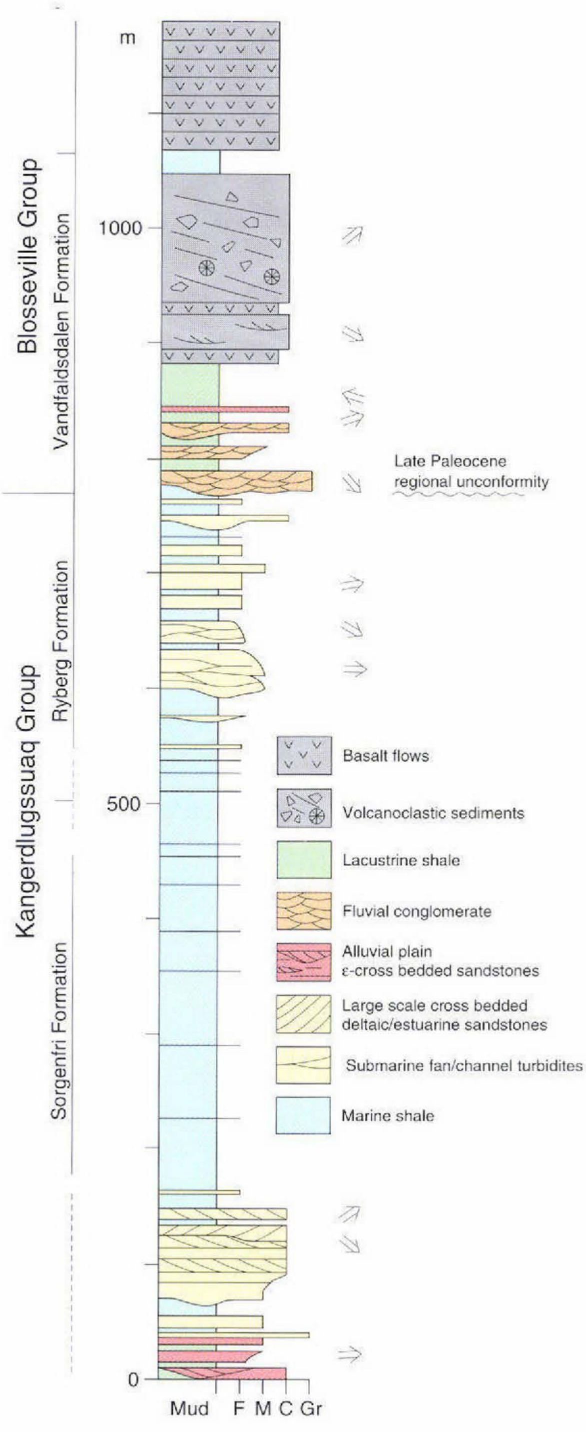

Fig. 3. Composite vertical section through the sedimentary succession in the Kangerlussuaq region. The succession reflects an initial mid-Cretaceous transgression and deepening followed by an overall shallowing during the Late Cretaceous – Early Paleocene. Late Paleocene uplift caused regional erosion and a change from marine to continental deposition. The succession is overlain by lava flows interbedded with volcanic sediments marking the onset of volcanism in the region.

The sandstone units consist of amalgamated turbidite beds showing sediment transport directions towards the south-east and south. The presence of belemnites, marine bivalves and dinoflagellate cysts in the fine-grained portions indicates deposition in a marine basin and the succession is interpreted as laid down in a submarine fan environment. The uppermost tens of metres indicate a rapid shallowing-upwards with hummocky cross-stratified sandstones interbedded with marine shales of the lower shoreface.

Continental deposits abruptly overlie the marine sediments and the change in depositional environment seems to mark an Upper Paleocene basin-wide uplift. The most prominent of these deposits is a white, trough cross-bedded, pebbly conglomerate bed, 8–20 m thick showing transport directions towards the east and south-east (Figs 3, 4). The pebbly sandstones are associated with black carbonaceous shales overlying rooted horizons and are interpreted as deposited in a braided river system. The erosional surface is correlated between a number of different sections in the Kangerlussuaq area. The clastic continental sediments are overlain by a thick basalt succession, which towards the east and north-east passes into subaqueously deposited, tuffaceous sediments and hyaloclastites of the Vandfaldsdalen Formation (Soper *et al.*, 1976; Nielsen *et al.*, 1981). Along the north-eastern margin of the basin, the volcanic part of the succession is represented by a continental succession of laminated carbonaceous mudstones that coarsen upwards into channelised sandstones showing palaeocurrent directions towards the west and north-west. These sediments have an upward increasing content of volcanic derived material. Coal beds, of which some are autochthonous with rootlets beneath, become abundant towards the top of the section, indicating deposition in a coastal plain and delta plain environment (Nørgaard-Pedersen, 1991, 1992).

Basin evolution

Based on preliminary analyses of sedimentological and stratigraphic data collected during the 1995 field season and previous work in the region, the Cretaceous – Early Tertiary evolution of the basin can be summarised as follows.

The sedimentary basin was formed during mid-Cretaceous extension. Basin margin uplift caused erosion of the hinterland and sand dominated sediments were shed into the basin and deposited in estuarine and shallow marine environments. During the Late Aptian the basin was transgressed, possibly in response to an overall rise in relative sea-level. This relative rise in sea-level continued during the Late Cretaceous and the basin developed into a relatively deep marine basin dominated by suspension fall-out and fine-grained sandy turbidites flowing from the north and north-east. Towards the Paleocene sediment influx increased dramatically and a unit of coarse-grained fluvial

Fig. 4. Fluvial pebbly sandstones forming steep bluff. The coarse grained sandstones were deposited in a braided river system, which during the Late Paleocene shed vast amounts of clastic sediments into the basinal areas south-east of the Kangerlussuaq region. The sediments are overlain by Paleocene hyaloclastites and columnar jointed basalts. Person for scale.

sediments prograded from the western and north-western basin margin. These fluvial sediments are underlain by an erosional unconformity which is recognised throughout the region. The unconformity marks a change from a marine to a dominantly continental basin, and probably reflects regional uplift prior to and during initial volcanism in the Late Paleocene.

The lower lava series and the volcanoclastic rocks appear to be confined to local sedimentary basins showing strong thickness variations and diverging palaeocurrents. They consist of hyaloclastites, breccias, tuffs and tuffaceous sandstones of subaqueous origin (Nielsen *et al.*, 1981). The volcanic activity continued into Eocene time, with the extrusion of a several kilometres thick continental plateau basalt succession over the entire region (see Brooks *et al.*, this report). The region was exposed to regional uplift and erosion during the mid-Oligocene (Brooks & Nielsen, 1982).

Future studies

The 1995 field work will form the basis for detailed sedimentological and sequence stratigraphic studies, which have implications for interpretation of the development of the East Greenland continental margin. The ongoing work is coordinated with DLC studies in the Kangerlussuaq region on basin evolution, tectonics and early rifting both onshore and on the continental shelf offshore. Future work will be concentrated on geochemistry, palynology and 3-dimensional description of sandstone bodies in a Lower Cretaceous reservoir-analogue measured during the 1995 field work. The section is superbly exposed and further studies on geometry and sedimentary structures based on multi-model stereographic profiles are planned.

Acknowledgements. The project was financially supported by the Danish Lithosphere Centre (DLC), SAGA Petroleum a.s. and Danish Oil and Gas Production A/S (DOPAS) on behalf of the Amarada Hess Faeroe Islands Group. It forms part of the project 'Resources of the sedimentary basins of North and East Greenland' supported by the Danish Research Councils.

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Conclusion of the 1:500 000 field mapping in eastern North Greenland

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The third and last field season of the mapping project in eastern North Greenland (1993–95) was completed with full accomplishment of all geoscientific goals. The programme included producing a general overview of the onshore geology of the region between Jøkelbugten and Kronprins Christian Land (78°–81°N) aiming at production of a 1:500 000 geological map sheet. The map (sheet 9 of the Survey's 1:500 000 Greenland series) will cover the last remaining area to be compiled at this scale in North and North-East Greenland. Field work was initiated in 1993 with a limited programme (Henriksen, 1994) and continued with a major field campaign in 1994 (Henriksen, 1995). The planning of the field work in 1995 was carried out as in 1993 and 1994 by the Geological Survey of Greenland (GGU), but following the merger of GGU with the Geological Survey of Denmark (DGU) on 1 June 1995, the field work itself was completed under the auspices of the new institute – the Geological Survey of Denmark and Greenland (GEUS).

In addition to establishing a general overview of the regional geology the project aimed at obtaining an evaluation of the economic geological potential of the region, in respect to both minerals and hydrocarbons (Stemmerik *et al.*, this report). The field activities co-ordinated by GEUS also included two glaciological projects, one in co-operation with the Alfred Wegener Institute (AWI), Bremerhaven, and the second (Hans Tausen Iskappe project) based on special funding from the Nordic Council of Ministers (Thomsen *et al.*, this report). GEUS was responsible for the logistical organisation of the field work on behalf of all groups. Logistic support was also given to three two-man teams of botanists, whose participation was organised via the Danish Polar Center (DPC).

The field work in 1995 was carried out during a two-month field season from late June to late August with participation of a total of 46 persons, including 27 geologists and 7 glaciologists. The work was supported by two helicopters and a small fixed wing Twin Otter aircraft, which operated from a tent base camp at Centrum Sø, south-west Kronprins Christian Land, the site also used in 1993 and 1994. In addition, the military outpost Station Nord was used as a logistic backup point and for transit during mobilisation and demobilisation.

Regional geological studies

Eastern North Greenland and North-East Greenland comprise rock complexes which reflect a geological development extending over 2000 million years; the oldest units are Early Proterozoic basement gneisses preserved within the Caledonian fold belt and the youngest Late Tertiary – Quaternary glacigenic deposits (Fig. 1). The region is dominated by the northern part of the East Greenland Caledonian fold belt, which encompasses both deep seated and high level rock units and sequences. An extensive Caledonian foreland region west of the fold belt comprises unfolded Middle Proterozoic to Lower Palaeozoic successions of sedimentary and volcanic rocks. Post-Caledonian sediments referred to as the Wandel Sea Basin include a sequence of Carboniferous – Tertiary sediments deposited in a series of sub-basins during continental break-up. These sediments are now found in the relatively low-lying coastal regions of eastern North Greenland, east of the up to 1800 m high alpine peaks of the Caledonian fold belt. The latter includes reactivated Lower Proterozoic crystalline basement rocks as well as folded and metamorphosed representatives of Middle and Upper Proterozoic sedimentary sequences and less disturbed parautochthonous Lower Palaeozoic sediments (Figs 1, 2).

The field work in 1995 covered most aspects of the regional geology, and included the following main projects:

- Structure and petrology of the crystalline complexes in the Caledonian fold belt.
- Petrology of eclogites in the Caledonian crystalline complexes; partly financed by the American National Science Foundation.
- Studies of thin-skinned deformation in the western parautocthonous areas of the Caledonian fold belt in Kronprins Christian Land.
- Stratigraphy and structural geology of the Middle Proterozoic Independence Fjord Group in the Caledonian fold belt.
- Stratigraphy and petrology of Middle Proterozoic basic volcanics in the foreland areas and their presumed metamorphic equivalents in the fold belt.
- Sedimentology, stratigraphy and structural geology of

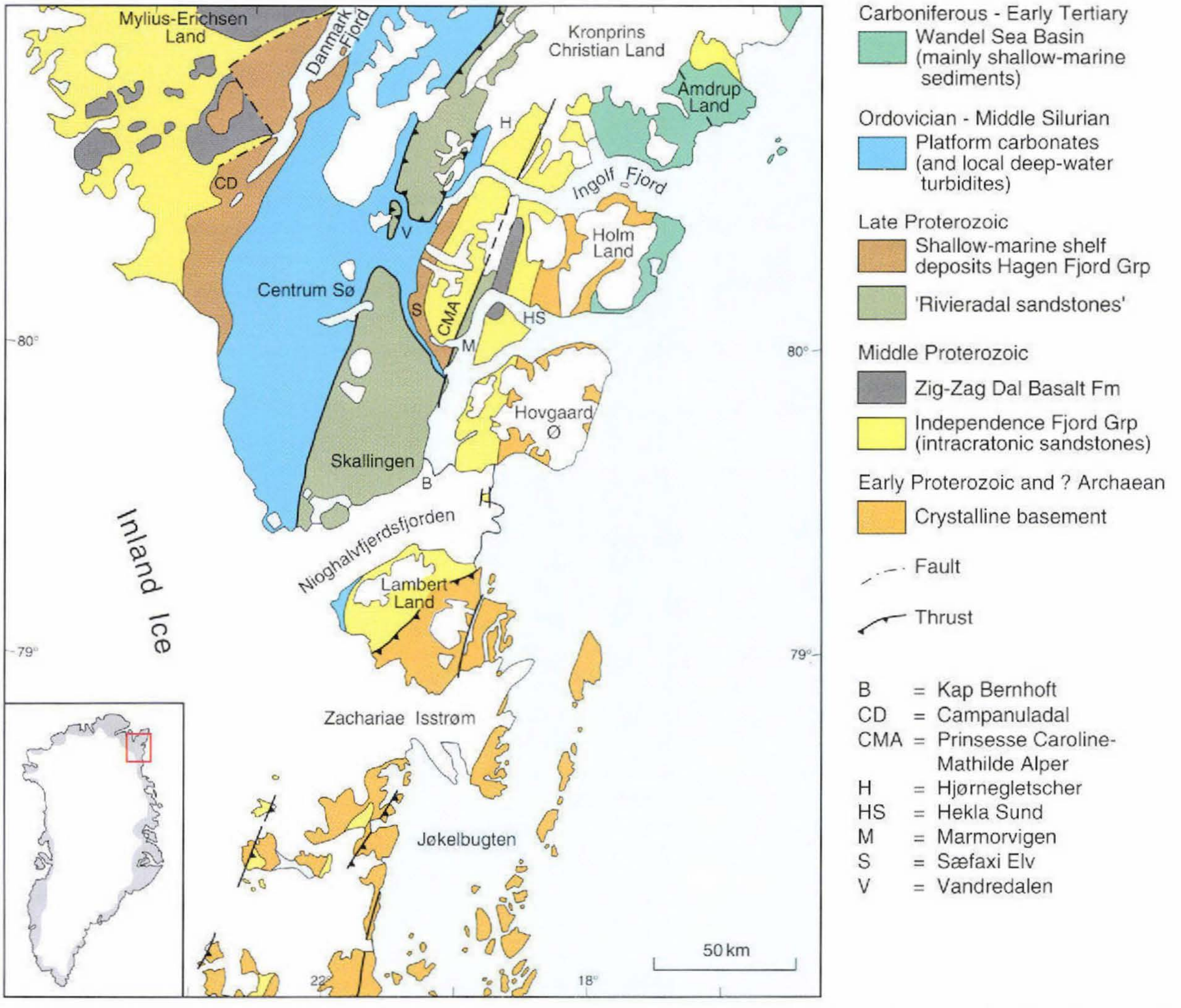

Fig. 1. Simplified geological map of the area covered by the 1:500 000 map Lambert Land 78°–81°N (sheet no. 9) in North-East and eastern North Greenland. Modified from Jepsen *et al.* (1994).

the Upper Proterozoic Rivieradal sandstone succession in Kronprins Christian Land; partly financed by the Carlsberg Foundation.

- Biostratigraphy and sedimentology of the Lower Palaeozoic carbonate sediments of Kronprins Christian Land; partly financed by the Carlsberg Foundation.
- Sedimentology and biostratigraphy of the post-Caledonian Upper Palaeozoic – Mesozoic sediments of the Wandel Sea Basin in eastern coastal regions of Kronprins Christian Land; partly financed by the Danish Ministry of Environment and Energy.

Preliminary results of the field work have been summarised by the participating geoscientists in an internal Survey report (Higgins, 1995), which forms the basis for the following presentation. The individuals responsible for the different aspects of this research are listed in the Appendix.

The core of the Caledonian fold belt comprises a variety of crystalline complexes which are widely exposed in the region between Jøkelbugten and Lambert Land (78°–79°N), and farther north found in poorly exposed outcrops in the coastal areas of Kronprins Christian Land. The crystalline complexes represent segments of the Precambrian Greenland shield (part of the North American Laurentian shield) which have been reactivated during the Caledonian orogeny. Two mapping teams continued their investigations of these rocks in 1995, with one team working in the south and north, while the second team concentrated on studies in the Lambert Land region (79°N).

The crystalline region in the south is dominated by Early Proterozoic ortho- and paragneisses, overlain by representatives of the Middle Proterozoic Independence Fjord Group (Jepsen *et al.*, 1994). Both units are dissected by abundant basic dykes and sills, which probably correlate with the 1250 Ma old Midsommersø Dolerites of North Greenland (Kalsbeek & Jepsen, 1983). The crystalline basement rocks have been subjected to an Early Proterozoic orogenic event, and all units have undergone regional deformation and metamorphism to at least amphibolite facies during the Caledonian orogeny. North-west of Jøkelbugten a tectonic window through a thrust sheet of amphibolite facies Lower Proterozoic basement gneisses reveals a broad area of Independence Fjord Group sandstones of lower metamorphic grade. Further important thrusts have been recorded to the west in the nunatak zone. The gneiss complexes are dominated by quartzofeldspathic, polyphase orthogneisses, including metamorphosed diorites, granodiorites, granites, tonalites and trondhjemites. Mafic rocks are abundant, and form pods, lenses, layers and bodies of amphibolite. Anorthositic and eclogitic units are also found in the crystalline complexes. In some areas the gneisses have suffered regional eclogite facies metamorphism, indicating that they were recrystallised at depths of 60–80 km in the crust. These eclogitic gneisses were subsequently retrogressed and are now generally found in association with amphibolite facies paragneisses. Supracrustal rock units occur as bands and lenses infolded with the crystalline gneisses. They are always strongly deformed, although some metabasites associated with the supracrustal rocks may preserve magmatic textures in their interior parts. Most of the supracrustal rocks are interpreted as representatives of the Middle Proterozoic Independence Fjord Group.

A detailed W–E traverse across the Caledonian fold belt through Lambert Land (*c.* 79°10′) to the islands off the coast to the east has confirmed the results of 1994 studies. The complex Caledonian nappe structure involves interleaving of crystalline basement and Proterozoic – Palaeozoic cover sequences. Four phases of Caledonian ductile deformation have been distinguished, including an early phase of northerly thrusting, followed by westward thrusting and later NNE–SSW shearing. The basement gneisses and overlying supracrustal rocks have similarities with the units found further south in the Jøkelbugten region. The presence of Caledonian intrusive rocks is inferred from lithological and structural relationships; an early foliated basic suite and a later unfoliated acid suite have been distinguished. Future isotopic studies may indicate whether these units are of Caledonian origin or older; the hitherto northernmost Caledonian intrusive rocks have been described from an area *c.* 400 km to the south of Lambert Land (Hansen *et al.*, 1994). Prominent anastomosing, NNE–SSW trending ductile shear zones can be traced along the west side of Jøkelbugten and in areas further northwards. The shear zones vary in width from nearly 1 km down to a few hundred metres, and juxtapose rock units of different crustal levels. They appear to be a continuation of the several hundred kilometre long Storstrømmen shear zone (Strachan & Tribe, 1994), an important structural feature throughout the region from Dronning Louise Land (76°N) northwards.

The detailed study of eclogites and related high pressure rocks in the Jøkelbugten region (Gilotti, 1994) has been continued; the eclogite terrain is now known to extend from south of Dove Bugt (77°N) to north of latitude 80°N, a region almost 400 km from north to south and 130 km from east to west; The occurrence of eclogites at present outcrop level indicates major geotectonic displacements since their formation at 60–80 km depth. A Caledonian origin, as indicated by some age determinations (Brueckner & Gilotti, 1993), implies there has been large scale Caledonian thrusting in the order of several hundred kilometres, or major late Caledonian differential uplift. The study of the eclogitic rocks and their surrounding rock complexes may hold the key to understanding the geotectonic setting of the East Greenland Caledonian fold belt and its relationships with other parts of the Caledonian fold belt around the North Atlantic.

The stratigraphy and structural geology of Middle Proterozoic successions within the Caledonian fold belt were investigated in the Prinsesse Caroline Mathilde Alper region. Extensive outcrops of sandstones correlated with the Middle Proterozoic Independence Fjord Group are present, as well as basalt sequences thought to represent the Zig-Zag Dal Basalt Formation and abundant dolerite intrusions; these units were involved in Caledonian folding and thrusting, and have undergone low grade metamorphism. A notable find was an up to 400 m thick basalt sequence within the Independence Fjord Group sandstones. In the foreland all the known Zig-Zag Dal Basalt Formation overlies the Independence Fjord Group sandstones, and the basalts have therefore been considered as entirely younger than the sandstones. Basic sills and dykes occur abundantly within the sandstone sequences in both the foreland and the fold belt, and are all correlated with the 1250 Ma old Midsommersø Dolerites (Kalsbeek & Jepsen, 1983).

The Upper Proterozoic 'Rivieradal sandstone' succession is confined to allochthonous Caledonian nappe units (Vandredalen thrust sheet) in the region between Lambert Land (*c.* 79°N) and northern Kronprins Christian Land (*c.* 81°N). The succession underlies units of the Hagen Fjord Group, although no precise correlations have been established (Hurst *et al.*, 1985). The study of the sedimentology of these sequences and an analysis of the basin development was initiated in 1994 and continued in 1995. In the western part of the Vandredalen thrust sheet detailed sedimentological studies of key sections were made within the upper part of the 'Rivieradal sandstone'. This part of the succession comprises at least 2000 m of alternating mudstones and sandstone/conglomerate dominated units. The mudstones and sandstones are mainly outer and inner shelf deposits, while the conglomerates are probably of fluvial

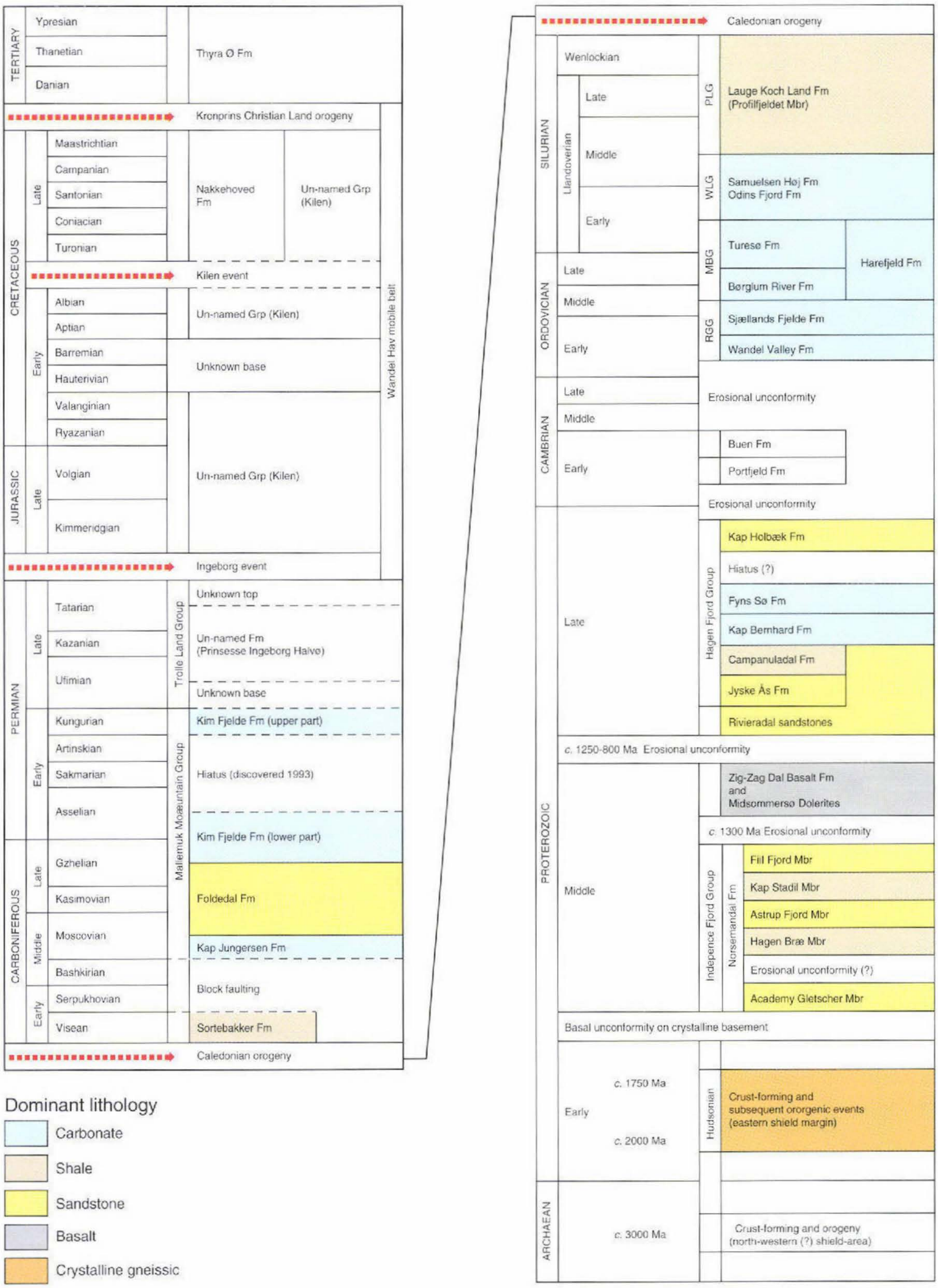

Fig. 2. Scheme showing principal events and lithostratigraphical divisions represented in eastern North Greenland. Colours: units occurring in the 1:500 000 map area 78°–81°N. RGG: Ryder Gletscher Group; MBG: Morris Bugt Group; WLG: Washington Land Group; PLG: Peary Land Group. Modified from Jepsen *et al.* (1994).

origin. On the east side of Vandredalen a more than 3000 m thick sequence of turbiditic mudstone and sandstone at a lower stratigraphical level reflects deep water deposition. The precise age and regional significance of this Upper Proterozoic sequence in North-East Greenland is still open for discussion; systematic collections of material for acritarch studies may help to resolve the age problem.

The studies of the thin-skinned deformation pattern in the parautochthonous areas carried out in 1993 (Jepsen *et al.*, 1994) and 1994 were continued in 1995; a model based on studies of the Vandredalen thrust sheet indicates a westward displacement in the order of 35–50 km for this structural unit. Work in 1995 concentrated on an east–west section across the Vandredalen thrust sheet in central Kronprins Christian Land, which will join up with a section through deeper structural levels spectacularly exposed in the cliffs along Ingolf Fjord. These structural studies show a strike parallel division into a series of zones separated by thrusts, with an increasing complexity in the deformation pattern from west to east. The structural style is clearly thin-skinned in the west, characterised by low angle thrusts with ramps and flats and varying fold intensities from place to place. Eastwards there is a transition into a zone with steeper, more deep-seated thrust units, characterised by intense folding (Fig. 3).

In southern Kronprins Christian Land, structural studies along a 50 km east–west section resulted in a division into three structural domains: a western zone of open upright folds, a central zone of west-verging overturned close folds, and an eastern zone of complex overturned folds and thrusts. However, only the upper and lower parts of the 'Rivieradal sandstone' succession seem to be represented in this section; a thick central part of the succession known farther north in Rivieradal appears to have been cut out here by thrusting.

The Lower Palaeozoic succession of East Greenland and eastern North Greenland was deposited at the western rim of the proto-Atlantic ocean (Iapetus). In Kronprins Christian Land the sediments comprise a sequence of Ordovician – Silurian dolomites, limestones and turbiditic mudstones which outcrop in a parautochthonous moderately to gently folded and thrust zone, west of and underlying the Vandredalen thrust sheet. Investigations in 1995 mainly concerned stratigraphical studies, including systematic collection of material for micropalaeontological studies of conodonts (Rasmussen & Smith, this report). The lowest part of the sequence in Sæfaxi Elv was found to correspond to known formations of the Ordovician Wandel Valley Formation, and not an allochthonous deep-water Silurian succession as suggested by Hurst & McKerrow (1985); the Sæfaxi Elv nappe distinguished by Hurst & McKerrow does not exist (Rasmussen & Smith, this report). In westernmost Lambert Land units of the Wandel Valley Formation were found to rest unconformably on the Independence Fjord Group, which demonstrates that the progressive overstep of the Early Ordovician from west to east across North Greenland (Peel & Smith, 1988) continues southwards into Kronprins Christian Land.

Stratigraphical and structural studies of the post-Caledonian Wandel Sea Basin (Håkansson & Stemmerik, 1995) were carried out in the outer coastal areas of Holm Land and Amdrup Land. Upper Palaeozoic sediments were the main target, but in addition the Mesozoic and Tertiary sediments in the northernmost part of Kronprins Christian Land were briefly visited.

In Holm Land Lower Carboniferous fluvial sediments were found to rest on Caledonian reworked Precambrian gneisses, and in northern Amdrup Land Upper Carboniferous sediments overlie isoclinally folded Independence Fjord Group rocks.

Economic geology investigations

The regional mineral resource reconnaissance programme was planned as a follow-up on geochemical anomaly indications resulting from the geochemical reconnaissance programme in 1993 and 1994, and anomalies detected by analytical studies of Landsat satellite images. The 1995 field work confirmed that the Middle Proterozoic Zig-Zag Dal Basalt Formation and parts of the Hagen Fjord Group sandstones have a potential for Cu mineralisation. In J. C. Christensen Land Cu mineralisation was found in a 60 m wide belt over a distance of 800 m in Hagen Fjord Group sandstones; an association with regional faults and links with the occurrence of Cu in the Zig-Zag Dal Basalt Formation is suspected. In 1994 surprisingly high Au values were recorded in Silurian carbonates; analytical results of 1995 sample collections from the same area are not yet available. Field observations suggest possible mineralisation could be related to thrust zones and associated karstic features (Carlite-type gold mineralisation). The spectral enhancement of the Landsat TM images indicated a number of anomaly zones with potential Fe-oxide staining or gossans. A number of these discoloured zones were visited, and in most cases were found to be rusty coloured exposures and shear zones without direct indications of mineralisation. The work on refining the enhancement of spectral signatures for various mineralisation indicators is to be continued in the light of the results from the field work.

Petroleum geological investigations were mainly focused in 1995 on the post-Caledonian sequences in the Wandel Sea Basin; studies of the Palaeozoic platform successions are also planned. Samples will be evaluated for thermal maturity, aiming at establishing a basin development model for both the Lower Palaeozoic foreland areas and the post-Caledonian Wandel Sea Basin. The conodont studies from

Fig. 3. Intense folding in Proterozoic sandstones and volcanic rocks, intruded by thick basic dykes and sills which are also folded. South side of Ingolf Fjord, Kronprins Christian Land.

the Ordovician – Silurian carbonates will reveal temperature indications (CAI values) and it is planned to undertake thermal maturity analyses and micropalaeontological investigations of the Upper Palaeozoic – Mesozoic and Tertiary units. The interest for oil geological evaluations of onshore outcrops should be viewed in relation to the existence of a very broad continental shelf offshore North-East Greenland which includes thick successions of Upper Palaeozoic – Tertiary sediments.

Co-operation with other institutions

The field work in 1995 involved a continuation of the close logistic and scientific co-operation with the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven. The glaciological programme on the glacier Storstrømmen, at the rim of the Inland Ice west of Danmarkshavn (*c.* 77°N), was continued with establishment of a number of automatic climate stations. Positions of a stake network established in earlier seasons were remeasured by GPS in order to measure ice movement and ablation, and radar reflectors for a SAR (Synthetic Aperture Radar Repeat Track Interferometer) experiment established in 1994 were repositioned. Ice samples were collected for chemical analysis. Additional AWI glaciological investigations were carried out at the rim of the Inland Ice southwest of Centrum Sø in Kronprins Christian Land. Here the main objectives were to remeasure the position of a stake line set out in 1994 in order to determine ice flow velocities and ablation, and to control and retrieve data from two automatic weather stations put up in 1994. Ice samples were collected from a profile line for isotope studies, and samples for measurement of dust concentrations, crystal size and chemical analysis were also taken.

Co-operation was also continued with a glaciological group working on Hans Tausen Iskappe, central North Greenland; this programme is funded by the Nordic Council of Ministers and the European Union's Third Framework Programme ENVIRONMENT in co-operation with the Danish Polar Center and the Survey (Thomsen *et al.*, this report). A 'mini-meteorite' study was undertaken on Hans Tausen Iskappe in 1995 by a French scientist, the objectives being to sample extra-terrestrial dust.

Three two-man teams of botanists from universities in Copenhagen and Münster, Germany, coordinated by the Danish Polar Center (DPC), were provided with logistic support by the Survey during a field campaign in the Kronprins Christian Land region. The three teams worked independently, mainly on studies of plants, lichens and mosses, and algae in lakes.

Logistic co-operation was also carried out with the mining company Platinova A/S, who continued their investigations of the lead-zinc deposit at Citronen Fjord in northern Peary Land. The co-operation included mutual use of helicopters and fixed wing aircraft in the Peary Land region.

Concluding remarks

The entire region between Jøkelbugten (78°N) and northern Kronprins Christian Land (81°N) is now known in sufficient detail to allow compilation of the planned 1:500 000 map. The three years of field work (1993–95) were completed according to plan and a general regional overview of the geology and the economic geological aspects has been obtained. Laboratory investigations continue, and the results will be documented in GEUS bulletins and maps and articles in international publications.

Appendix. The 1995 field parties were:
Crystalline complexes: J. C. Escher & J. D. Friderichsen (GEUS), K. A. Jones (Oxford Brookes Univ., UK), J. M. Hull (Seattle Central Community College, USA).
Eclogite studies: S. Elvevold (Univ. Tromsø, Norway), J. A. Gilotti (Geol. Survey, New York State Museum, USA).
Zig-Zag Dal Basalt Formation (Middle Proterozoic): H. F. Jepsen & S. A. S. Pedersen (GEUS), L. E. Craig (The Open Univ., Leeds, U. K), B. G. J. Upton (Univ. Edinburgh, UK).
Independence Fjord Group (Middle Proterozoic): S. A. S. Pedersen (GEUS), L. E. Craig (The Open Univ., Leeds, UK), A. G. Leslie (Queen's Univ. Belfast, UK).
'Rivieradal sandstones' (Upper Proterozoic): M. Sønderholm (GEUS), H. Tirsgaard (Mærsk Olie & Gas, Copenhagen).
Caledonian deformation: A. K. Higgins, H. F. Jepsen & S. A. S. Pedersen (GEUS), A. G. Leslie (Queen's Univ. Belfast, UK), N. J. Soper (Univ. Sheffield, UK).
Lower Palaeozoic carbonates (and conodonts): J. A. Rasmussen, (GEUS), M. P. Smith (Univ. Birmingham, UK).
Wandel Sea Basin: F. Dahlhoff, S. Piasecki & L. Stemmerik (GEUS), B. D. Larsen (Aarhus Univ., Denmark).
Mineral resource reconnaissance: M. Lind & T. Tukiainen (GEUS).
Petroleum geological investigations: F. Dahlhoff & S. Piasecki, (GEUS).
Glaciological investigations (North-East Greenland): C. E. Bøggild (GEUS), F. Jung-Rothenhausler & H. Oerter (AWI, Bremerhaven, Germany).
Glaciological investigations (Hans Tausen Iskappe): O. B. Olesen & H. H. Thomsen (GEUS), P. Jonsson (Lund University, Sweden), N. Reeh (DPC, Copenhagen).
Mini-meteorite study: M. Maurette (Univ. Paris, France).

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N. H., Geological Survey of Denmark and Greenland, Copenhagen

Lower Palaeozoic carbonates in eastern North Greenland, and the demise of the 'Sæfaxi Elv nappe'

Jan Audun Rasmussen and M. Paul Smith

As participants in the three-year 1:500 000 mapping programme in eastern North Greenland initiated in 1993 by the Geological Survey of Greenland (Henriksen, 1995, this report), the principal aim of the authors was to document the stratigraphy and structure of Ordovician and Lower Silurian sediments in a *c.* 5000 km² area in southern Kronprins Christian Land and westernmost Lambert Land (Fig. 1), and estimate the palaeogeographical position of Greenland in relation to the areas surrounding the Iapetus Ocean. The area studied lies within the East Greenland Caledonian fold belt, in the parautochthonous boundary zone between far-travelled nappe sheets and undisturbed foreland sediments.

Geological setting

The Lower Palaeozoic sediments of Kronprins Christian Land and Lambert Land were deposited on a subtidal to peritidal carbonate platform which constituted the easternmost part of the Franklinian Basin that extended from the Canadian Arctic islands across North Greenland (Higgins *et al.*, 1991). The stratigraphy erected in Peary Land and western Kronprins Christian Land (Peel, 1985; Higgins *et al.*, 1991; Smith & Bjerreskov, 1994) can, to a significant degree, be applied to the successions farther to the east and south within the study area (Fig. 2), although many of the units differ in detail. Eastern Kronprins Christian Land was affected by the Caledonian orogeny, and the Lower Palaeozoic units of the study area make up the parautochthonous foreland in the footwall of the Vandredalen thrust sheet. The parautochthonous succession, which comprises the Ordovician Wandel Valley, Sjælland Fjelde and Børglum River Formations, the Upper Ordovician to Lower Silurian Turesø Formation, and the Lower Silurian Odins Fjord, Samuelsen Høj and Lauge Koch Land Formations, is disrupted by thrust sheets with generally small displacements. Good stratigraphic control of the superficially similar looking alternating units of peritidal dolostone and subtidal burrow-mottled limestones is essential, and was achieved in the field by detailed sedimentary facies analysis and macrofaunal biostratigraphy. This will be followed up by the biostratigraphic analysis of conodonts to verify field determinations.

The 'Sæfaxi Elv nappe' and the Harefjeld problem

One of the initial field work objectives was to investigate the sediments of the 'Sæfaxi Elv nappe' of Hurst & McKerrow (1981), which was thought to comprise allochthonous deeper water equivalents of the Upper Ordovician – Lower Silurian carbonate platform sediments to the west (Hurst & McKerrow, 1981, 1985; Hurst *et al.*, 1985), and to examine an apparent conflict between these accounts and the earlier work of Fränkl (1954, 1955).

Hurst & McKerrow (1981, 1985) recognised a thrust sheet containing Ordovician – Silurian carbonates thrust over the Proterozoic Fyns Sø Formation, and structurally underlying the Vandredalen thrust sheet containing the 'Rivieradal sandstones'. The carbonates were thought to belong to the Danmarks Fjord Dolomite (abandoned name), which was subsequently assigned to the Lower Ordovician Danmarks Fjord Member of the Wandel Valley Formation by Peel *et al.* (1981) and Smith & Peel (1986). These shallow water carbonates were thought to be overlain by deep water carbonates of probable Silurian age assigned to the Harefjeld Formation by Hurst (1984) (Figs 3, 4A). The apparently marked contrast with known foreland successions, which contain only shallow water Ordovician – Silurian sediments, was explained by a proposed transport distance in excess of 100 km (Hurst & McKerrow, 1981, 1985).

In contrast to this interpretation, Fränkl (1955) had earlier recognised an unconformable, tectonically undisturbed, boundary between the Fyns Sø Formation and the Danmarks Fjord Member with a sandstone above the unconformity and sandstone-filled fissures extending downwards into the Fyns Sø Formation.

The Proterozoic – Palaeozoic boundary was examined at a locality 5 km to the west of Marmorvigen where the Danmarks Fjord Member shows relationships to the Fyns Sø Formation very similar to those described by Fränkl (there is evidence to suggest that it may be the same locality). A 1.8 m thick coarse- to very coarse-grained quartz arenite rests on the unconformity surface with a 10–15 cm imbricated conglomerate at the base. The conglomerate clasts are mainly composed of Fyns Sø Formation litholo-

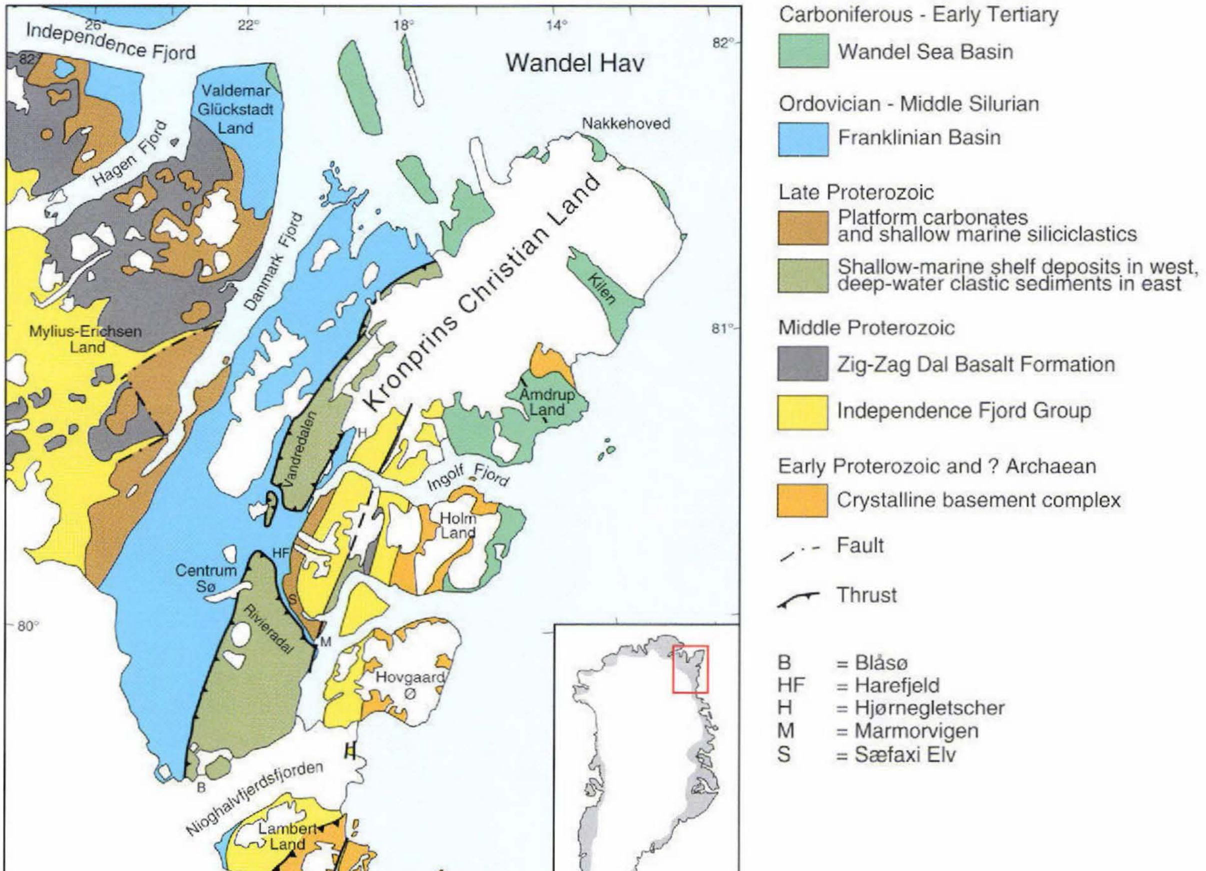

Fig. 1. Geological sketch map of Kronprins Christian Land and Lambert Land.

gies but there are also some coarse-grained quartz arenite clasts. The sandstone passes gradationally upwards into a burrow-mottled dolostone, and the sandstone itself is bioturbated in its upper part. Little relief was seen on the unconformity surface and there is no perceptible angular discordance between the Fyns Sø Formation and the overlying Danmarks Fjord Member. Early Ordovician conodonts have been recovered from samples of the Wandel Valley Formation taken at localities on both Harefjeld and in Sæfaxi Elv.

Beneath the sandstone, vertical to sub-vertical fissures extend down into the Fyns Sø Formation and appear to connect with a network of 1–2 m diameter sub-horizontal tubes up to a maximum of 10 m below the unconformity surface; the latter are interpreted as a fossil cave system. Both fissures and tubes are filled with well-cemented quartz arenites of coarse sand to granule grain sizes. The presence of these fissures connecting with the sandstone at the base of the Danmarks Fjord Member rules out the possibility of a thrust at this boundary.

In summary, there is no evidence for a thrust at the base of the Palaeozoic sequence and as the successions in Sæfaxi Elv and on Harefjeld itself can be unequivocally assigned to the Wandel Valley Formation, it is recommended that the Harefjeld Formation of Hurst (1984) is abandoned. The Sæfaxi Elv nappe does not exist, and the sediments once assigned to it may be regarded as part of an intact footwall sequence underlying the Vandredalen thrust sheet.

Extension of the Early Ordovician overstep

The Lower Ordovician Wandel Valley Formation is the oldest Palaeozoic lithological unit found in Kronprins Christian Land. It comprises three members. The lower member, the Danmarks Fjord Member, includes an up to 10 m thick evaporitic collapse breccia.

East of Vandredalen, the Danmarks Fjord Member is overlain by highly strained burrow-mottled lime mudstones (*c.* 200 m) in which the burrows are considerably stretched (Figs 3, 4A). These have yielded conodonts of late Early Ordovician age and are assigned to the Amdrup Member of the Wandel Valley Formation. This member is in turn overlain by recessive dolostones of peritidal origin (115 m) containing Whiterockian conodonts, together indicative of

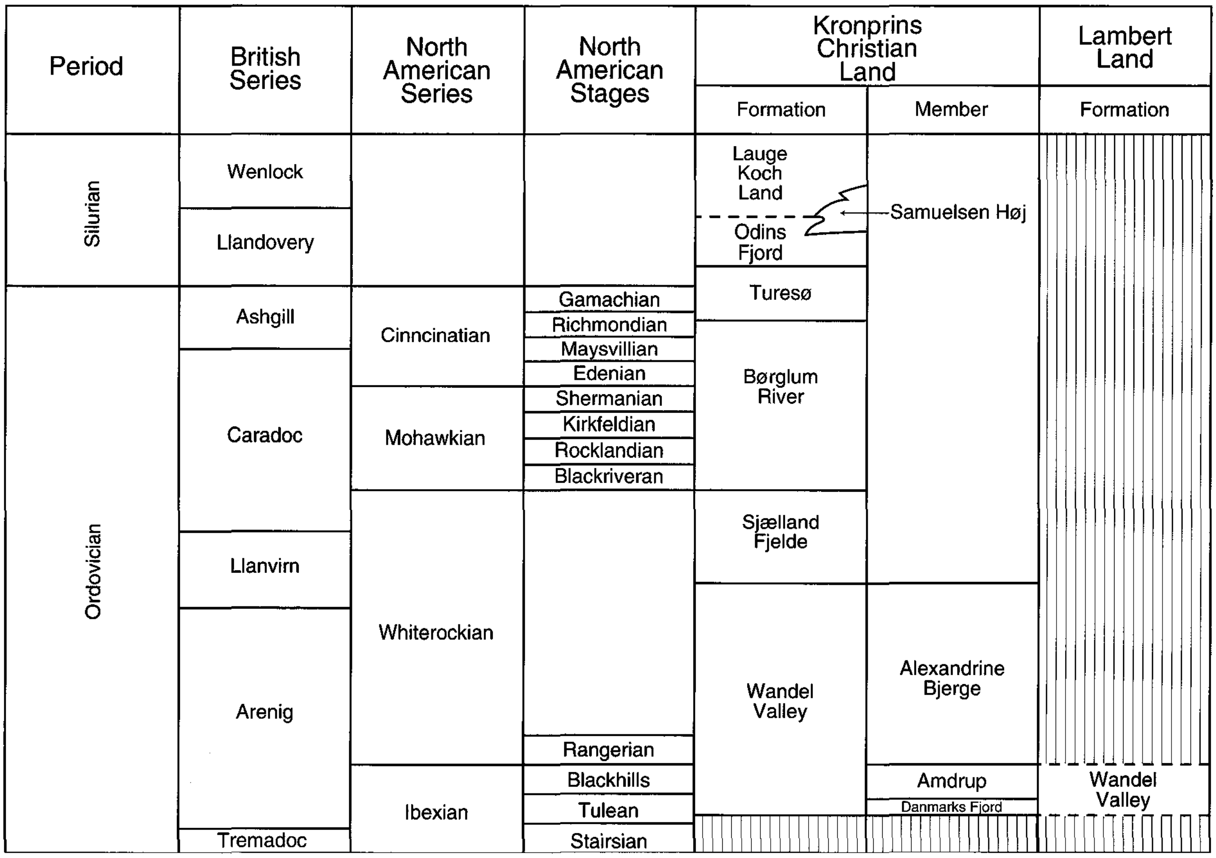

Fig. 2. Lower Palaeozoic stratigraphy of Kronprins Christian Land and Lambert Land.

the Alexandrine Bjerge Member (Fig. 3). In summary, all three members of the Wandel Valley Formation in the Sæfaxi Elv – Harefjeld – Ingolf Fjord area are very similar to their development in the type area around Danmark Fjord on the foreland.

Prior to the current mapping programme, the Wandel Valley Formation was not known to crop out south of Kronprins Christian Land. However, strongly sheared outcrops of carbonates found in westernmost Lambert Land in 1994 were shown to be Palaeozoic in 1995.

Examination of the quartzite–carbonate boundary near the Inland Ice margin demonstrated that the carbonates in question do unconformably overlie Independence Fjord Group quartzites with very slight angular discordance. The basal 25 m of the carbonates constitute a generally pale weathering unit which is made up of current laminated dolostones with scours and some ripple lamination together with darker wavy laminated dolostones with ripples and drapes (Fig. 4B). Some cyclicity is evident, and the top of one cycle contains probable pseudomorphed evaporite nodules. This lower unit is overlain by highly sheared, dark-weathering wavy laminated and burrow-mottled, somewhat dolomitised, carbonates. A rock sample from the lower unit contained a small number of phosphatic, organic fragments of which four have been positively identified as broken, coniform conodont elements indicative of an Ordovician age for the unit. The conodont fragments are black which corresponds to CAI 5 (conodont Colour Alteration Index), suggesting a post-depositional heating of the sediments of 300–480 °C (Rejebian *et al.*, 1987).

Taking into account the lithofacies present, the unconformable relationship with the underlying Independence Fjord Group, and the recovery of fragmentary conodonts, the Lambert Land carbonates are here assigned to the Wandel Valley Formation. Measurements of the strontium-calcium ratio and the manganese content as part of a preliminary chemostratigraphic programme, give further evidence for this interpretation (see below). It is probable that the lower 25 m unit represents the Danmarks Fjord Member and that the upper unit is part of the Amdrup Member. The thickness of the upper unit in Lambert Land is difficult to estimate due to structural complications, but it does not exceed the 200 m seen in the Amdrup Member in Kronprins Christian Land.

Fig. 3. Harefjeld viewed from the south showing steep or cliff-forming burrow-mottled limestones of the Amdrup and Danmarks Fjord Members of the Wandel Valley Formation (WV), which unconformably overlies the Fyns Sø Formation (FS). The recessive pale weathering cap of the hill is the lower part of the Alexandrine Bjerge Member (AB, Wandel Valley Formation).

Chemostratigraphy applied to Lower Palaeozoic carbonates

The biostratigraphical studies associated with the project are mainly based on conodonts, which are the most abundant fossil group throughout the Ordovician and Lower Silurian succession. However, conodonts are rare or absent in coastal marine environmental settings, which means that alternative stratigraphical methods must be considered in these cases.

The potential of chemostratigraphy based on carbonate trace-elements has been known for more than two decades. Hitherto, the studies have been concentrated especially on Mesozoic and Cenozoic sediments such as Cretaceous chalk (Jørgensen, 1975, 1986), and Tertiary pelagic sediments (Renard, 1986). Provisional studies show that chemostratigraphy can add information of the relative age of low-grade metamorphosed, Lower Palaeozoic, peritidal carbonates in eastern North Greenland.

Concentrations of calcium (Ca), magnesium (Mg), strontium (Sr) and manganese (Mn) were determined by a Perkin-Elmer Atomic Absorption Spectrophotometer, and the preparation of sample solution and standards was carried out in accordance with normal procedures for determination of elements in the carbonate fraction of limestone. Subsequently, the Sr/Ca and Mg/Ca ratios, and the Mn ppm content were computed and graphically displayed, following the procedure of Jørgensen (1986). The method has the advantage of being both cheap and quick.

Fifty samples were collected from the Wandel Valley, Sjælland Fjelde, Børglum River, Turesø and Odins Fjord Formations in order to test the method (Fig. 5).

The amount of analysed material is as yet far too small to provide a basis for a chemical zonation scheme, but some apparent trends seem to exist. For example, the burrow-mottled Børglum River and Odins Fjord Formations, which are difficult to distinguish from each other in the field, seem to be separated both on the Sr/Ca ratio and the manganese content. The Sr/Ca ratio is significantly higher within the Børglum River Formation than in the overlying Turesø and Odins Fjord Formations (Fig. 5), and in addition, the manganese content is considerably lower in the latter two formations than in the Børglum River Formation, except for the two lowermost samples of the Turesø Formation. It

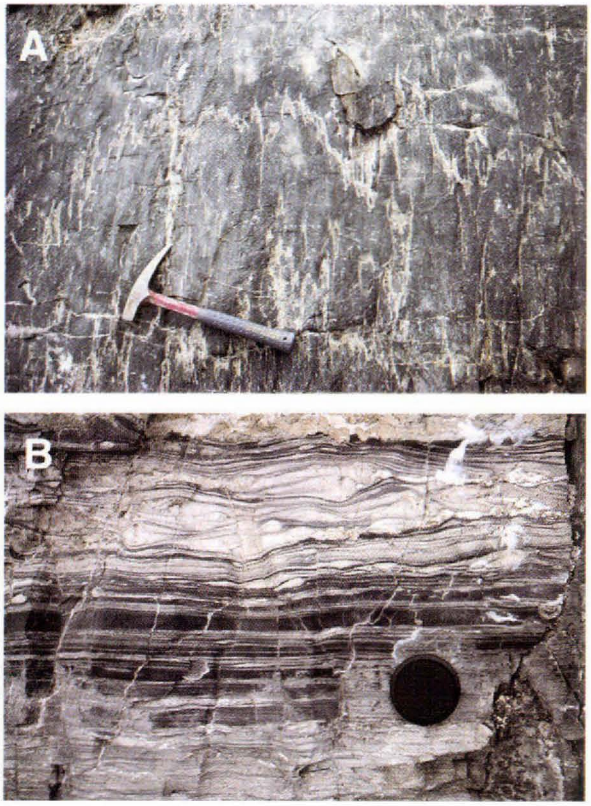

Fig. 4. A: Vertical stylolites in highly strained burrow-mottled facies of the Amdrup Member (Wandel Valley Formation) on Harefjeld. B: Highly strained wavy laminated facies in the basal part of the Wandel Valley Formation (equivalent to the Danmarks Fjord Member) in westernmost Lambert Land. Horizontal, cylindrical, dolomite-filled burrows are seen in cross-section.

is possible that the significant drop in the Sr/Ca ratio and the manganese content in the lower part of the Turesø Formation are related to the significant glacio-eustatic sea-level drop just below the Ordovician – Silurian boundary and the succeeding transgression. Another possibility is that the Sr/Ca ratio changes are influenced by an accelerated hydrothermal activity, which gives an increased Ca concentration in the sea water, finally resulting in a lowering of the Sr/Ca ratio (Renard, 1986).

The manganese content is extremely high in some intervals in the Danmarks Fjord Member and the Alexandrine Bjerge Member (> 200 ppm), a characteristic which seems to be restricted to these two units (Fig. 5).

Four samples from the newly discovered conodont-bearing Ordovician sediments in western Lambert Land were analysed (the 'DF?' and 'AM?' samples in Fig. 5). The DF? sample is characterised by a high manganese value and a medium high Sr/Ca ratio. These values are similar to the values measured from one of the Danmarks Fjord Member samples collected at Danmark Fjord. The succeeding Lambert Land samples ('AM?') show relatively high Sr/Ca ratios and a low manganese content. This pattern is also displayed by the Amdrup Member (AM) and the lowermost part of the Børglum River Formation (BR). Field relations make the Amdrup Member the most likely alternative.

The Mg/Ca ratio is mainly dependent on the dolomite/calcite ratio in the sample, meaning that it has a limited stratigraphical value in this sedimentological setting where alternating dolostone and limestone beds are common. In contrast, the Sr/Ca ratio is not affected significantly by the dolomite/calcite ratio.

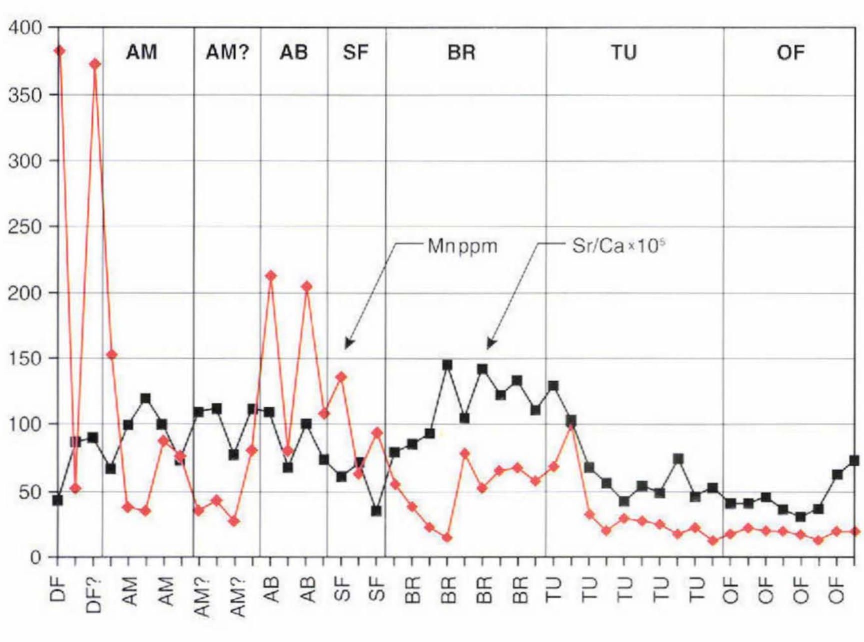

Fig. 5. Evolution of the strontium/calcium ratio and the manganese content in Ordovician and Lower Silurian carbonate samples from eastern North Greenland. DF: Danmarks Fjord Member (Wandel Valley Formation), DF?: probable Danmarks Fjord Member (Lambert Land), AM: Amdrup Member (Wandel Valley Formation), AM?: probable Amdrup Member (Lambert Land), AB: Alexandrine Bjerge Member (Wandel Valley Formation), SF: Sjælland Fjelde Formation, BR: Børglum River Formation, TU: Turesø Formation, OF: Odins Fjord Formation.

In conclusion, it is possible to separate between many, but not all, the studied lithological units based on Sr/Ca and manganese chemostratigraphy. The method can clearly distinguish between the quite similar burrow-mottled, limestone-dominated units, the Middle to Upper Ordovician Børglum River Formation and the Lower Silurian Odins Fjord Formation, as the former unit has a higher Sr/Ca ratio, and commonly also a higher manganese content.

Future work

Detailed sedimentological logging, together with the collection of more than 330 conodont samples through most parts of the investigated Ordovician and Lower Silurian succession, will form the basis for further stratigraphic and basin evolution studies as well as conodont palaeoecological and palaeogeographical analyses. The chemostratigraphic pilot-study suggests it may be possible to establish a chemostratigraphic zonation through the Franklinian Basin carbonate succession in northern Greenland provided a more extensive analysis programme is undertaken.

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Distribution of gold, arsenic, and antimony in West and South Greenland: a guide to mineral exploration and environmental management

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The search for gold deposits has been a part of human activity as far back as history goes. The most popular exploration method for gold has been panning, a technique still widely used in both exploration and exploitation. In the first half of this century, geochemical exploration methods based on chemical analysis of systematically collected samples were developed and used successfully in the search for a range of ore deposits. However, direct geochemical exploration for gold (Au) was not feasible until the 1980s due to the insufficiency of analytical methods to determine the very small concentrations of Au in common rocks and surficial deposits.

In the early period of geochemical exploration arsenic (As) and antimony (Sb) were commonly used as so called pathfinder elements for Au (Boyle, 1979). The name is given because of the common association of gold mineralisation with rocks enriched in arsenopyrite (FeAsS) and/or stibnite (Sb_2S_3), and because As and Sb were easier to determine analytically due to their higher abundances. Many cases reported in the literature have documented the frequent association of Au with As and Sb, and As and Sb anomalies in geochemical surveys are still considered indicative of gold mineralisation, particularly where the anomalies coincide (e.g. Plant *et al.*, 1991). However, more and more cases are also described where Au mineralisation is not associated with As and Sb. For example this applies to shear or fault zone hosted Au deposits in granitoid rocks.

Ten to twenty years ago the analytical situation with regard to Au improved with the introduction of neutron activation techniques, flameless atomic absorption spectrometry and other methods; today analyses for Au, As and Sb are carried out on a routine basis and at low cost with the result that these elements are commonly determined in geochemical surveys. The numerous analyses achieved worldwide have immensely improved our knowledge of the distribution of Au, As and Sb as geochemical elements in the natural environment. This is also the case in Greenland where the Geological Survey of Denmark and Greenland analysed all systematically collected stream sediment samples by Instrumental Neutron Activation Analysis for a range of elements including Au, As and Sb. The large scale regional distribution patterns for the three elements are shown here for the first time, and their implications for gold exploration and for environmental issues are discussed.

Outline of the geology

The Precambrian of West and South Greenland comprises rock complexes from early Archaean to Mesoproterozoic in age (Escher & Pulvertaft, 1995; see Kalsbeek 1994 for an overview containing the latest isotopic evidence). Most of the area consists of gneiss complexes of Archaean age which have been variably affected by Proterozoic deformation and metamorphism. Basic metavolcanic and metaplutonic rocks are common as enclaves within the Archaean gneisses throughout West Greenland, whereas intercalations of basic metavolcanic rocks together with metasediments occur at Taartoq, Nuuk and Torsukattak. Metaigneous and metasedimentary rocks formed during the Proterozoic occur in the three Palaeoproterozoic orogens, the Ketilidian in South Greenland, the Nagssugtoqidian, and the Rinkian from Torsukattak and northwards. In addition, Proterozoic platform volcano-sedimentary sequences occur in the Midternæs – Grænseland region in South-West Greenland (Fig. 1). South Greenland was further subjected to Mesoproterozoic rifting and alkaline magmatism within the Gardar province.

Data acquisition and presentation

The samples were collected under the Survey's reconnaissance geochemical mapping programme of Greenland. The programme uses systematically collected samples of stream sediment and stream water. The fine fractions (< 0.1 mm) of the sediment samples are analysed for a minimum of 40 major and trace elements whereas the conductivity and fluoride concentration are determined in the water samples (Steenfelt, 1987,1993a). The results have hitherto been reported in GGU's *Open File Series* and *Thematic Map Series* (see list of 1994 publications included with this volume). However, each of these publications only covers a small section of Greenland, hence very large scale geochemical variations are not seen. The first compilation of stream sediment data from a contiguous area from Uummannaq to Kap Farvel was published by Steenfelt

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(1994a). It showed that the distribution patterns of the major elements Ca and K reflect important crustal boundaries such as suture zones between continents, and that the data can be used to characterise the tectono-stratigraphic elements of the Precambrian crust (Steenfelt, 1994b).

The 5635 stream sediment samples used in this presentation were collected over a period of 15 years (see Steenfelt, 1994a). Each sample is a composite of 3 to 10 subsamples collected at different places in the stream bed along 10 to 50 m of the stream course. The sampling density is 1 sample per 6 km^2 in western South Greenland and 1 sample per 20 to 30 km^2 in other areas. Samples were analysed for As, Sb and Au by Instrumental Neutron Activation Analysis (INAA) at Activation Laboratories Ltd or by Bondar-Clegg Laboratories, both in Canada. The lower limit of detection for the analyses is 5 ppb for Au, 2 ppm for As and 0.2 ppm for Sb.

The results are displayed as dot maps (Figs 1, 2) where each dot represents a sample location where the concentration is above detection limit; the dot size is proportional to the measured concentration. The scaling of the dot size is chosen so that the regional variations are illustrated as well as possible. Table 1 lists statistical parameters for the data together with estimates of the crustal abundance of the elements.

Table 1. Percentiles of Au, As and Sb concentrations in stream sediment samples from West and South Greenland

%	Au ppb	As ppm	Sb ppm
10	0	0	0
20	0	0	0
30	0	0	0
40	0	0	0
50	0	0	0
60	0	0	0
70	0	2	0.2
80	0	4	0.4
90	6	9	0.6
95	9	16	0.9
98	15	40	1.4
99	26.5	71	1.8
av*	3.89	3.53	0.23
max	850	1100	36.4

* see text for method of calculation

Average abundances

Figures for crustal abundances of elements may be useful for studies of crust–mantle relationships, for global mass-balance calculations, and as a basis for chemical comparisons between various parts of the crust. However, published figures (e.g. Taylor, 1964; Wedepohl, 1969–1979; Taylor & McLennan, 1985) are all estimates based on limited numbers of samples. As more analytical data emerge these estimates may need revision. The region dealt with here represents a substantial proportion of the Precambrian crust of Greenland and the average concentrations for Au, As and Sb may, therefore, contribute to the improvement of existing estimates for crustal abundance.

Many of the measured concentrations are below the detection limits for the three elements (Table 1), hence it is not possible to obtain true average figures or to display the true geochemical background variation throughout the region. An estimate of the true average has been obtained by assuming that the average of element concentrations below detection limit is equal to half the value of the detection limit: 2.5 ppb for Au, 1 ppm for As and 0.1 ppm for Sb. The resulting average abundance estimates for the three elements in stream sediment are then 3.89 ppb Au, 3.53 ppm As and 0.23 ppm Sb for the Precambrian of West and South Greenland. Equal area representation was used in the calculation of these figures to ensure that the result is not biased by the higher density of samples in western South Greenland.

The abundance of the three elements in the upper crust is estimated by Taylor & McLennan (1985) at 1.8 ppb Au, 1.5 ppm As and 0.2 ppm Sb. The figures from West and South Greenland agree for Sb but are considerably higher for Au and As. The higher Au abundance in stream sediment is expected because gold grains are resistant to weathering and their abundance increases in the stream environment relative to that of the surrounding rocks.

Geochemical data from a comparable section of Precambrian crust is provided by the Geochemical Atlas of Finland (Koljonen, 1992). The averages of *c.* 300 till samples collected systematically over the whole of Finland are 1.2 ppb Au, 3.3 ppm As, and 0.3 ppm Sb. Again As averages are much higher than the estimate by Taylor & McLennan (1985) and this leaves the possibility that they have underestimated the magnitude of As mineralisation in the upper crust. Otherwise it must be concluded that the two areas of Precambrian crust are enriched in As.

Distribution patterns in relation to geology

The maps demonstrate that the three elements As, Sb and Au are very unevenly distributed over West and South Greenland and also that there are significant differences in their distribution patterns (Figs 1, 2). The As distribution shows a small number of well defined high-As provinces, the Sb distribution shows several clusters but also some scatter, whereas the Au distribution appears to be the most even with poorly outlined clusters and elevated values scattered over the entire region.

The high As provinces and clusters are clearly associated with certain rock complexes: the Archaean supracrustal rocks around Torsukattak in the north and at Taartoq in the south, the Proterozoic supracrustal rocks in Midternæs – Grænseland, and the southern supracrustal sequences of the Ketilidian orogen. The common feature of these rock complexes is that they comprise metasediments interlayered with volcanic rocks. In addition, elevated As values occur associated with mafic to ultramafic rocks near Paamiut, and scattered high values occur within the granite dominated part of the Ketilidian orogen. In the remaining part of Greenland the stream sediments have very low concentrations of As, close to or below 2 ppm. The Nagssugtoqidian orogen is also largely barren with the exception of a few samples derived from mafic metavolcanics in the Nordre Strømfjord shear zone. This is in strong contrast to the high As signature of the Ketilidian orogen.

Thus, it appears that high As characterises volcano-sedimentary deposits of both Archaean and Proterozoic ages. Other supracrustal sequences characterised by high As concentrations include the Palaeoproterozoic Karrat Group of meta-greywackes north of Uummannaq (Thomassen, 1992) and equivalent formations within the Foxe fold belt on Baffin Island (Cameron, 1986), the Neoproterozoic Eleonore Bay Supergroup in East Greenland (Steenfelt, 1993b) and the equivalent Dalradian in Scotland (Plant *et al.*, 1991). Based on comparative studies of supracrustal sequences Simpson *et al.* (1989) have suggested that build up of As concentrations is characteristic of rapidly subsiding extensional basins where As is supplied by volcanic emissions and is retained by organic, sulphur-rich compounds. The As abundance may therefore be seen as an indicator of a certain type of geological environment, which in Greenland distinguishes the supracrustal sequences at Taartoq and Torsukattak from all other Archaean supracrustal formations.

The distribution of Sb is far less relatable to particular lithological units than is the case for As. In South Greenland the clusters of high Sb values largely, but not entirely, coincide with the high As province and anomalies; the distribution patterns of As and Sb in South Greenland are shown in greater detail in Steenfelt & Tukiainen (1991). Further north significant discrepancies are noted between As and Sb concentrations. The As-rich Midternæs volcano-sedimentary sequence is low in Sb as are the mafic rocks east of Paamiut, whereas Sb anomalies occur in As-low areas just north and south of Paamiut.

Scattered Sb anomalies occur between Nuuk and Sisimiut in the As-barren region dominated by Archaean orthogneiss. The small Sb cluster at the Sarfartôq carbonatite-kimberlite occurrence suggests that ultrapotassic rocks such as kimberlites and lamprophyres may be the source of the Sb. In fact the entire region east of Maniitsoq is a province of kimberlite and lamprophyre dykes (Larsen & Rex, 1992). At Torsukattak the Sb anomalous samples are derived from both Archaean and Proterozoic rock complexes, unlike the high As samples which are confined to the Archaean rocks in that area. The introduction of Sb to the Proterozoic sediments could reflect a remobilisation of Sb-bearing deposits in Archaean layers, or could be caused by ultrapotassic magmatism as discussed by Steenfelt (1992).

A great deal of 'noise' in the Au analytical results is expected for the following reasons: (1) The minute but dense gold grains are very irregularly distributed in the stream bed leading to non-representative sampling. (2) Sample amounts submitted for analysis are very small (1 to 7 g), so that measured gold concentrations are poorly representative of the entire sample ('nugget effect'), particularly at low concentrations. (3) Analytical precision is poor close to the detection limit.

These uncertainties imply that where gold is detected in stream sediment samples there has to be gold in the stream surroundings, but the actual values obtained in the samples cannot be considered proportional to the quantities of gold in the drainage basin. On the other hand, the absence of gold in a sample does not necessarily mean that there is no gold in the area. At the scale of this presentation the scattered 5 ppb samples may be disregarded and attention focused on the distribution of higher values.

The elevated Au values are scattered over most of the map area with higher density towards north and south. A large proportion of the Au anomalies fall within the high As provinces, but many high Au values do not coincide with either high As or high Sb. Nor do they appear to be related to any particular rock complex or any particular geological environment.

Implications for mineral exploration

Arsenic and Sb are both brought to the surface environment by volcanic activity. Owing to their affinity with sulphur and carbon they are retained in organic-rich sedimentary basins, particularly under reducing conditions. This is expressed in abundance figures for As and Sb in various rock types (Table 2). The behaviour of Au is less well known, but it may be assumed that Au follows As and Sb and is upgraded in organic-rich sedimentary environments. Such sedimentary deposits can be regarded as crustal reservoirs for Au, As, Sb and other elements with similar behaviour (e.g. Mo, Cu, Bi) which may then act as source rocks for later mineralisation (Simpson *et al.*, 1989). The Greenland data suggest that the south-eastern Ketilidian sedimentary basin constitutes a typical crustal reservoir for Au with a potential for formation of gold deposits during later remobilisation and redeposition. Recent field work within the SUPRASYD programme has confirmed Au and As enrichment in graphite and sulphide rich pelitic layers, and several Au mineralised veins, with and without As, have been located in second-order structures adjoining major shear zones (Garde & Schønwandt, 1995; Stendal *et al.*, 1995). One gold vein prospect with economic potential is known (Petersen & Pedersen, 1995), but the large number of samples with elevated and high Au concentrations within the high As province (Fig. 1) strongly suggests that more deposits of this kind are to be expected.

Antimony is known to be easily mobilised from its primary setting through transportation by and redeposition from hot hydrous solutions. Consequently, the present distribution pattern of Sb is likely to outline areas of hydrothermally mineralised fracture systems centred on late granitic, alkaline or perhaps lamprophyric/kimberlitic magma intrusions. In areas where a supracrustal source of Sb is missing the magmas themselves may be assumed to have supplied the Sb. In many documented cases Au has also been mobilised and redeposited during hydrothermal activity. However, the lack of spatial correlation between Au and Sb anomalies over West and South Greenland outside the Ketilidian sedimentary basin suggests that Sb alone is not a useful pathfinder element for gold.

Even slight elevations in Au and As may be significant and reflect economic gold mineralisation, e.g. the small As and Au anomalies at Storø (Fig. 2) where a promising gold prospect is being drilled (Petersen *et al.*, 1995). The gold prospect occurs in the sheared boundary zone between the Akulleq and Akia terranes, and the other gold anomalies along this boundary suggest that gold mineralisation may also be found in other parts of this zone.

Pathfinder elements outline one type of environment with gold potential, but the Au

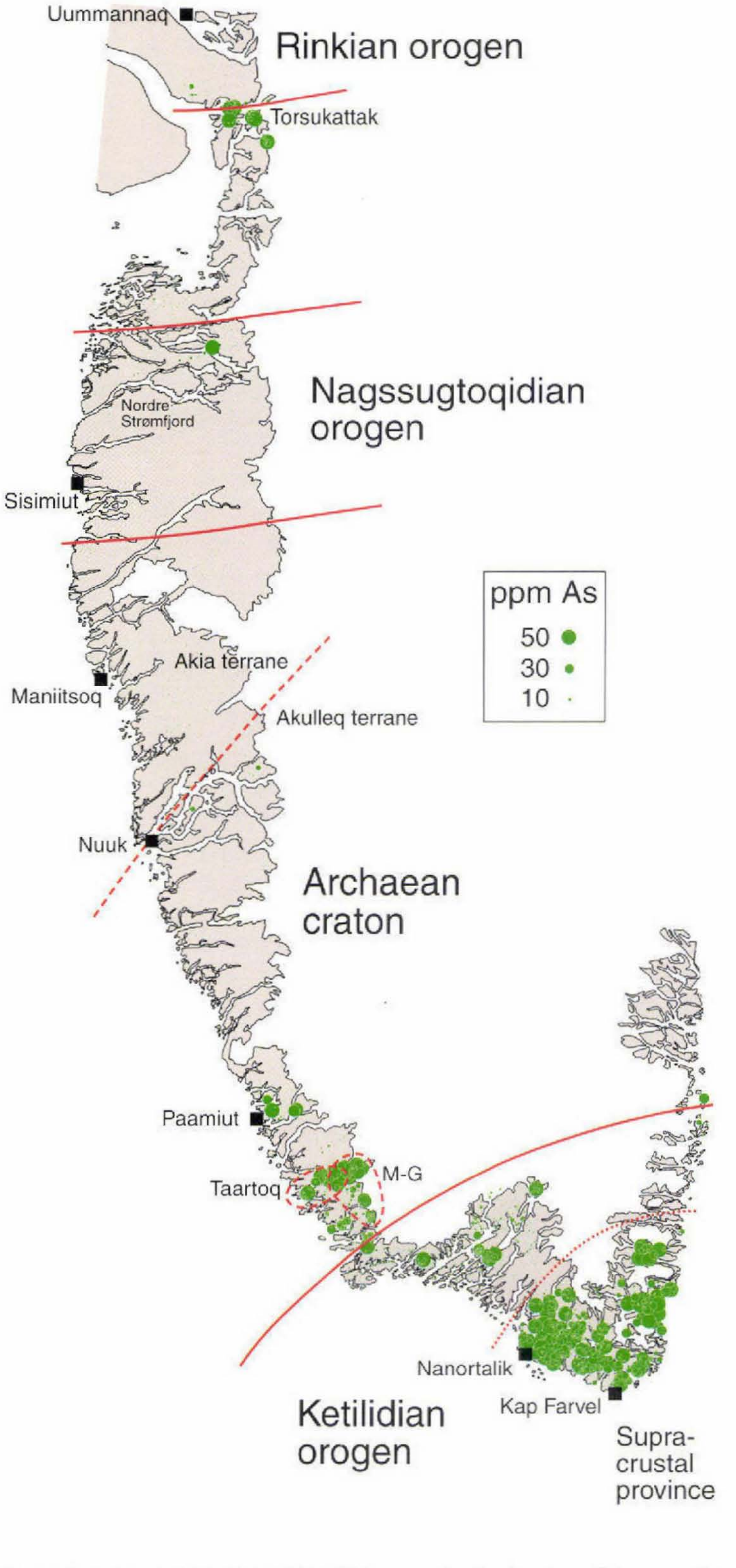

Fig. 1. Arsenic concentrations of the <0.1 mm grain size fraction of stream sediment samples. Instrumental neutron activation analysis. M–G: Midternæs – Grænseland.

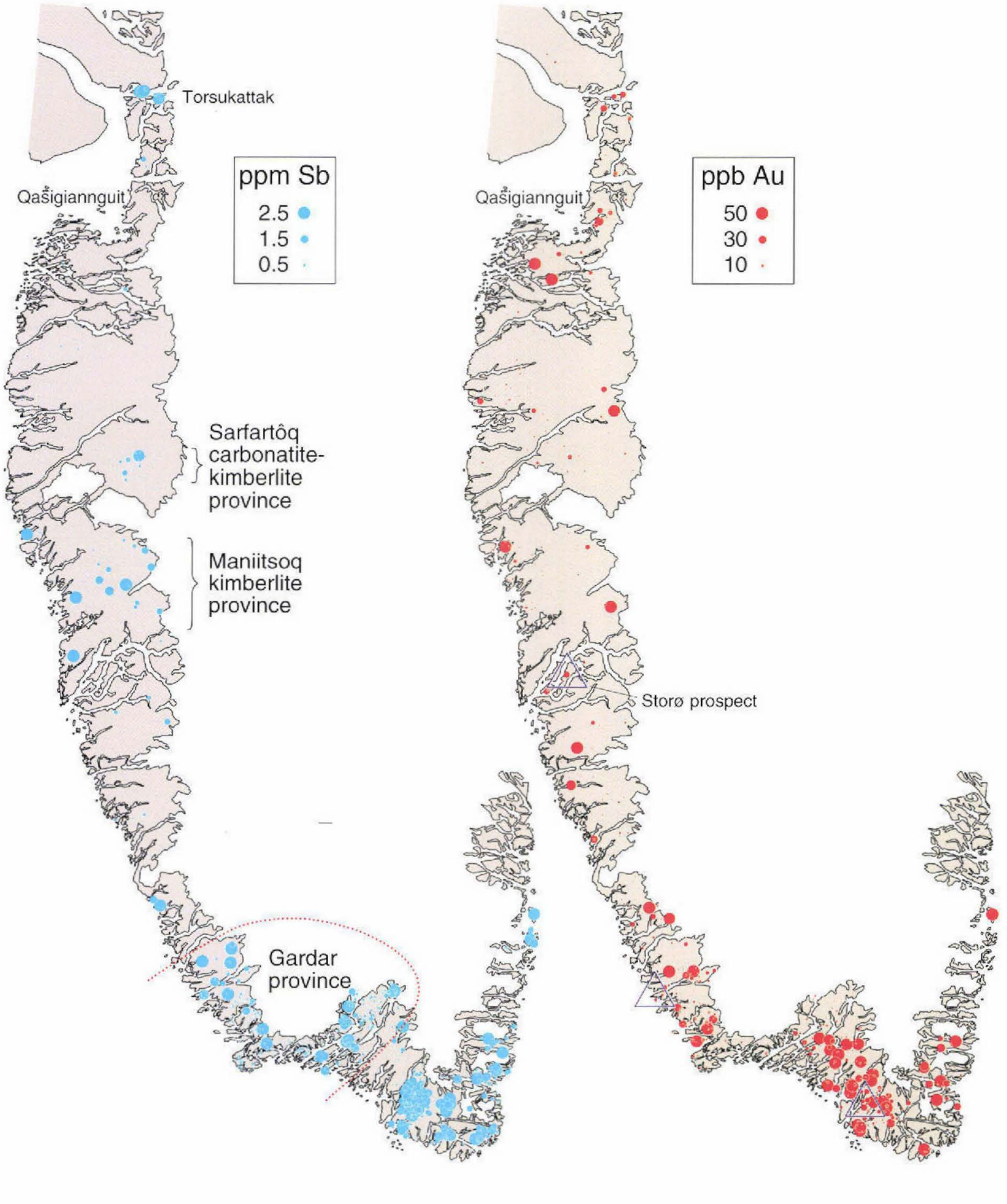

Fig. 2. Antimony (Sb) and gold (Au) concentrations of the <0.1 mm grain size fraction of stream sediment samples. Instrumental neutron activation analysis. Drilled gold prospects are shown by open triangles.

Table 2. Abundance of Au, As and Sb in common rock types (Govett, 1983) and estimates of crustal abundance (Taylor & McLennan, 1985)

	Au ppb	As ppm	Sb ppm
Igneous rocks			
Mafic	4	2	1.0
Intermediate	1	2.4	0.2
Felsic	1	0.25	0.1
Sedimentary rocks			
Shale	1	6.6	2.0
Upper crust	1.8	1.5	0.2
Crust	3.0	1.0	0.2

distribution itself suggests that a number of other types of mineralisation have taken place in various parts of Greenland. More studies are warranted to evaluate the significance of many of the scattered Au anomalies, but a few comments can be made at this stage. Thus fault systems and alteration zones associated with Mid-Proterozoic Gardar rifting and magma intrusion are suggested as possible sites for gold mineralisation. A cluster of elevated Au values associated with a sequence of metasediments near Qasigiannguit suggests that some kind of gold mineralisation has taken place there (see also Steenfelt, 1992).

Implications for environmental management

Both As and Sb belong to the group of elements which are potentially toxic in high concentrations, hence many government authorities have decided on upper limits for permitted concentrations of these elements in soil, water, industrial waste, crops etc. The value chosen as the upper acceptable limit for a particular element is typically based on the average abundance of this element in a given natural medium, e.g. soil and water. However, the geochemical maps of As and Sb show that the regional variation in the natural geochemical background is so large that the use of any average figure as a measure of the natural background at a particular place is meaningless. For example, industrial waste containing 10 ppm As would be 10 times 'dirtier' than the natural background in the Maniitsoq district, but would be about 4 times 'cleaner' than the average natural background in the Nanortalik district.

Pollution, defined as artificial additions to nature which raise the concentration of a particular element to a level above the natural background, cannot be defined properly without documentation of the regional variations in the element concentrations. The geochemical maps presented here provide such a documentation on a regional scale and also serve to outline areas where the natural concentration of a particular element may warrant attention from the authorities. In the case of potentially toxic elements such as Sb, Cd and Pb concern should be directed to areas of high concentrations, whereas in the case of elements with nutritional value such as K, Mg and Zn it is important to identify areas where abnormally low concentrations may cause deficiency problems for plants and plant eating animals.

Data on soil may be considered more relevant to environmental research than stream sediment data. However, studies of stream sediment and soil analyses from within the same area show that element concentration levels for the two media are similar. Only elements such as Zr, Y, Th, which are essentially contained in weathering resistant, accessory minerals, are enriched in stream sediment relative to the surrounding soil.

Conclusion

The compilations of Au, As and Sb data over large parts of the Precambrian of West and South Greenland provide an overview of large scale distribution patterns which are relevant to geological interpretation, mineral exploration and environmental monitoring. The large datasets also contribute to improving estimates of crustal element abundances.

South Greenland stands out as being particularly enriched in all three elements, which is interpreted to reflect primary accumulation of the elements in Palaeoproterozoic volcano-sedimentary basins with subsequent remobilisation and redeposition during both the Ketilidian orogeny and the Mesoproterozoic Gardar rifting and alkaline magmatism. Arsenic and Sb may be used as pathfinders for Au in this province and in Archaean greenstone belts, but the Au distribution suggests that a number of other types of gold mineralisation exist which are not associated with either high As or high Sb.

The documentation of the uneven distribution of As and Sb is essential to environmental management and shows the importance of knowing the local natural background concentrations at the site where environmental impacts of human activities are considered.

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Inglefield Land 1995: geological and economic reconnaissance in North-West Greenland

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Field work in Inglefield Land, North-West Greenland in 1995 (Figs 1, 2) was a direct result of an airborne magnetic and electromagnetic survey – project AEM Greenland 1994 (Stemp & Thorning, 1995a, b), the results of which stimulated considerable economic interest in the region. This survey not only delineated a large number of magnetic and electromagnetic anomalies (Fig. 3) in the Precambrian basement indicating a potential for massive sulphide mineralisation, but through video application it also drew attention to dark coloured, circular structures in central Inglefield Land. These structures were originally recognised during photogeological studies by RTZ Mining and Exploration Limited (Sharp, 1991). The recognition that the circular features formed a well-defined belt started fervent speculation that they might represent a volcanic pipe swarm (Bengaard, 1995; Stemp & Thorning, 1995a). The geophysical data and the region's potential for kimberlite pipes, created considerable interest from the international mining industry (Minex, 1995a) and commercial exploration under new exploration licences was undertaken in 1995 (Coppard, 1996).

With this background it was felt that the state should monitor the exploration developments in Inglefield Land, and consequently the Government of Greenland, Minerals Office agreed to fund a 4 million kr. follow-up project. This project, carried out by the Geological Survey of Denmark and Greenland, had the main objectives of explaining the geophysical anomalies and circular structures. Apart from the study of the latter, the field work comprised locating selected anomalies by GPS navigation and relating the sites to the regional geology, as well as ore geological studies and geochemical mapping.

This paper describes the field campaign in Inglefield Land and the general geological results obtained. The circular structures were proved to be surficial deposits by RTZ Mining and Exploration Ltd (Coppard, 1996), an interpretation confirmed by our study of the features (Appel, this report).

Logistics

Inglefield Land is an uninhabited 7000 km² area situated some 100 km north of Qaanaaq (Danish Thule) and 200 km north of Thule Air Base (Pituffik; Fig. 2). It is bordered by the Inland Ice to the south and east, and by Nares Strait to the north and west. Geomorphologically, the area forms a gently northwards dipping plateau of rolling relief dissected by streams running from the Inland Ice to the sea. There are no permanent ice caps but extensive areas are covered by glacial drift that is especially profuse in southern parts.

Mobilisation for the field work was through Thule Air Base. The lack of a suitable, centrally placed site with fixed-wing aircraft landing facilities demanded aerial reconnaissance by Twin Otter in early July prior to the geological work. An excellent locality was found on a large, vegetation-covered sand terrace south of the eastern lake of Septembersøerne in eastern Inglefield Land (78°50.60′N, 67°18.03′W). A 250 m long strip was prepared and during the following week equipment and fuel were flown in and a tent base camp erected (Fig. 1). Five geologists, three assistants, and a helicopter pilot and mechanic made up the field party. Demobilisation in mid-August was by helicopter via Qaanaaq; the landing strip markings and a small depot of jet fuel remain on site.

Field work

The field work, carried out by three teams during a five-week period of excellent weather, was by helicopter reconnaissance supplemented by traverses from fly camps.

One team, concentrating on the Precambrian shield terrain, combined a check of selected geophysical anomalies with a reconnaissance of the regional geology and mineralisation. A photogeological map at 1:100 000, and geophysical maps from project AEM Greenland 1994 formed the basis for this work (Bengaard, 1995; Stemp & Thorning, 1995a).

A second team studied the circular structures (Appel, this report) and later investigated a number of magnetic anomalies and rust zones.

A third team carried out a geochemical programme that spanned eleven days of intensive, helicopter-supported systematic stream sediment and stream water sampling with an average sample density of 1 per 25 km². Soil was collected as a substitute medium in areas without streams. Major and trace element analyses are reported by Steenfelt & Dam (in press).

Fig. 1. The Survey base camp south of Septembersøerne seen from the west; orange gossan visible in right background.

Bedrock geology

The earliest regional geological investigation of Inglefield Land was carried out between 1917 and 1922 (Koch, 1920, 1933). Koch distinguished the main geological elements of the region: a Precambrian crystalline basement of varied lithology overlain by a undeformed Proterozoic and Lower Palaeozoic cover restricted to the outer coast. He also noted the large stretches covered by glacial drift in central and southern parts of Inglefield Land (Fig. 2).

Apart from sporadic visits to inland areas by way of the Inland Ice from the Thule district, early work was concentrated on coastal districts, particularly on the sedimentary cover rocks (Troelsen, 1950; Cowie, 1961; Dawes, 1972; Peel *et al.*, 1982). Information on the Precambrian shield remained very sporadic, and the summaries published (Dawes, 1976; 1988) were based essentially on the coastal areas of south-western Inglefield Land between Kap Alexander and Rensselaer Bugt. Apart from a few studies carried out by commercial companies (see below under '*Mineralisation*'), the 1995 helicopter reconnaissance of Inglefield Land was the first regional appraisal of the Precambrian shield.

Three main complexes make up the shield: the Etah Group supracrustal rocks, the Etah meta-igneous complex and a variable gneiss group. All three complexes show wide lithological diversity and they have been metamorphosed under high amphibolite to granulite facies conditions.

The Etah Group is composed of marble, calc-silicate rocks, pelitic schists and gneisses, and psammitic rocks including siliceous garnet gneisses. Metasediments in conspicuous linear tracts dominate the geology in south-western Inglefield Land. The Etah Group, that is also present in Ellesmere Island, Canada, is of Early Proterozoic (Late Aphebian) or Archaean age.

The Etah meta-igneous complex is a multiphase plutonic suite containing a range from ultramafic and basic rocks to syenites and granites. The complex, also present in neighbouring areas of Canada, has yielded Early Proterozoic ages from 1960 Ma to 1850 Ma (Dawes *et al.*, 1988; Frisch & Hunt, 1988).

The variable gneiss group contains both paragneisses and orthogneisses, derived from the above-mentioned complexes, as well as other migmatitic rocks. Quartzo-feldspathic, garnet (-sillimanite) gneisses outcropping over large areas of central and eastern Inglefield Land are part of this group. Some of the gneisses are of Early Proterozoic age, but it is unknown whether older material is also represented.

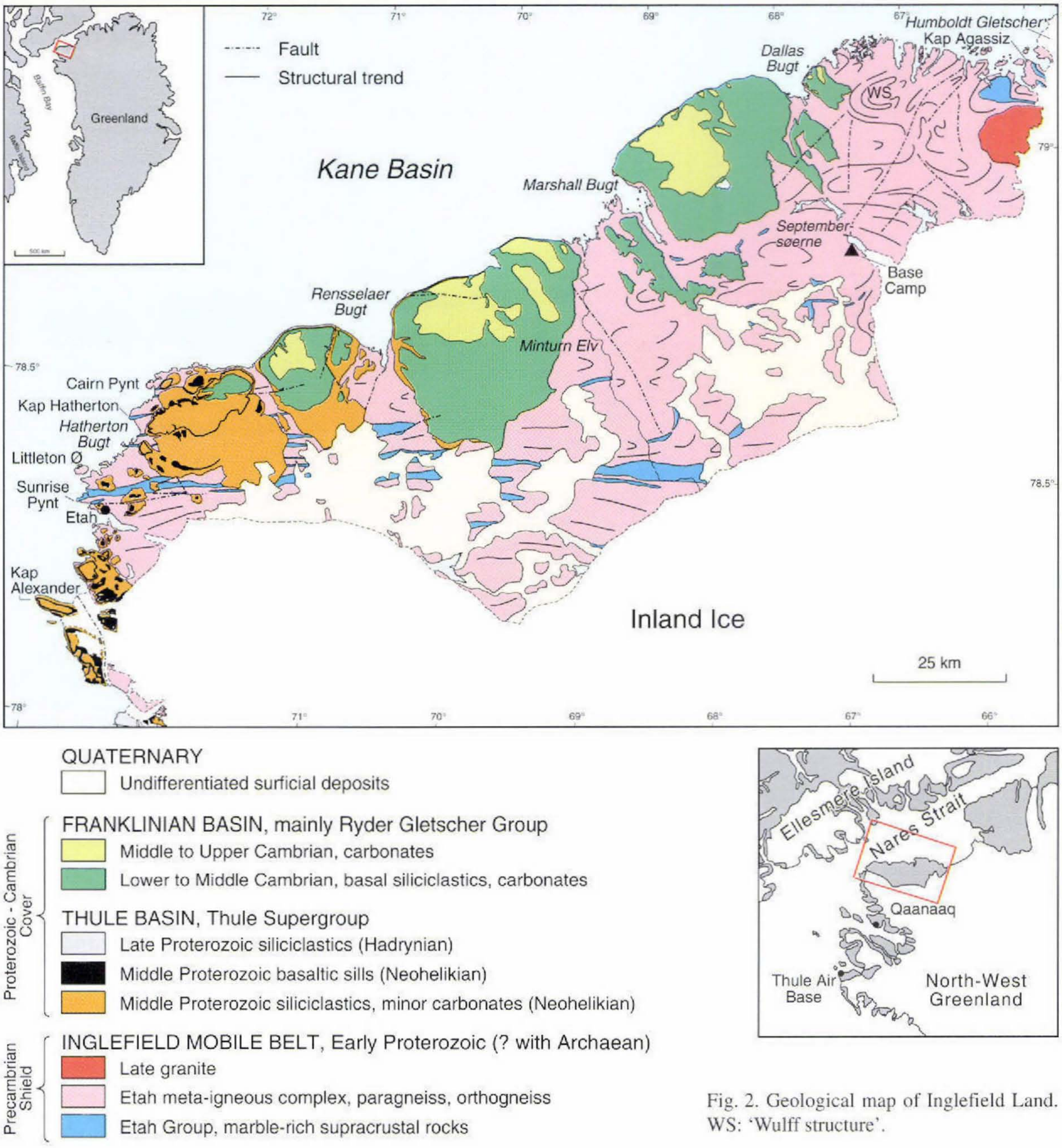

Fig. 2. Geological map of Inglefield Land. WS: 'Wulff structure'.

The 1995 field work demonstrated that the three complexes, all well known from south-western Inglefield Land and part of a regionally conspicuous linear belt, can be recognised farther eastwards across Inglefield Land to Humboldt Gletscher. Thus, the spectacular cliff section at Sunrise Pynt across the steeply-dipping linear belt of metasediments and igneous rocks, that has been used to illustrate the regional geology (Dawes, 1976, fig. 228; Dawes, 1988, fig. 3), has a counterpart in north-eastern Inglefield Land at Kap Agassiz (Fig. 4A). Here highly-deformed pale marble and calc-silicate rocks of the Etah Group are intruded by less-deformed grey and red granite sheets and younger dykes of the Etah meta-igneous complex. Marble-dominated supracrustal rocks form several such outcrops south-east and south-west of Kap Agassiz (Fig. 2). The encroachment of metasedimentary rocks by igneous rocks occurs on all scales. Thus, marble and calc-silicate rocks occur as part of coherent supracrustal belts, as well as as isolated tracts and inclusions within igneous rocks.

A glance at the geological map (Fig. 2) shows that, in

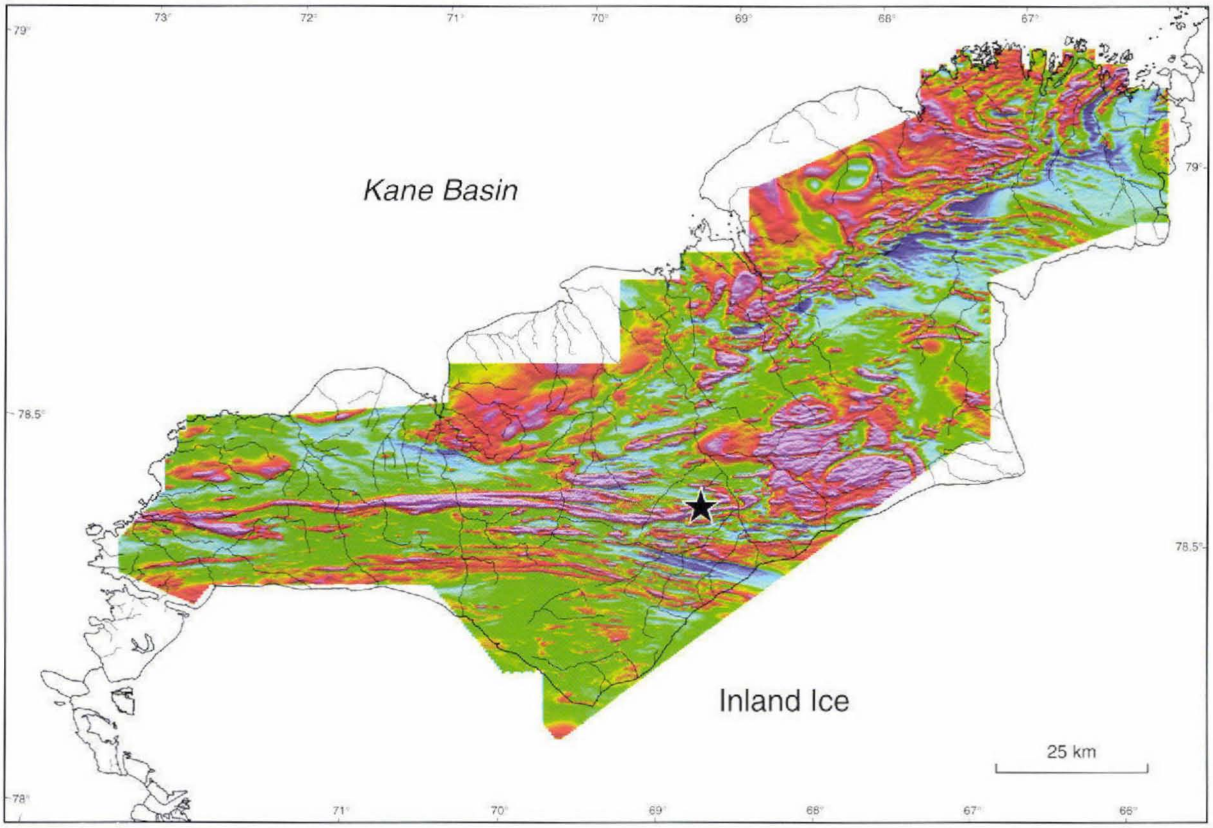

Fig. 3. Residual intensity magnetic anomaly map for part of Inglefield Land. The strongest magnetic anomaly in the area is indicated by a star. Modified from Appel *et al.* (1995).

contrast to south-western and north-eastern areas, much of central Inglefield Land – the hinterland of Marshall Bugt and Dallas Bugt – lacks conspicuous marble-dominated supracrustal rocks. In this area, multiphase magmatic rocks of the Etah meta-igneous complex dominate, and these rocks have been involved in polyphase deformation that has produced complex fold patterns such as the 'Wulff structure' (Fig. 2). The 1995 observations show that marble and calc-silicate rocks form small, scattered outcrops throughout this central region; their broken-up and isolated form is due to disintegration and assimilation by magmatic rocks.

It has been suggested that the Precambrian shield of Inglefield Land is composed of two distinct rock complexes: a southern one characterised by marble-dominated supracrustal belts and recessive gneisses, and a northern, homogeneous complex of resistant gneisses and granites with minor supracrustal rocks (Bengaard, 1995). This model, that hints at the possibility of two terranes separated by a discontinuous belt of granitoid rocks, is not supported by earlier observations, nor by the 1995 field work or the geophysical data (R. W. Stemp, personal communication, 1995). Marble-rich supracrustal rocks having the same relationships to igneous rocks occur both in the northern and southern areas. Along the well-known south-western coast of Inglefield Land (Frisch & Dawes, 1982), this speculative boundary is drawn by Bengaard (1995, fig. 1) north of the major marble unit at Kap Hatherton. However, the presence of known marble units intruded by the same red granitic rocks as along the coast north of Kap Hatherton (one marble unit is included by Bengaard), militates against any fundamental break in the geology between Etah and Cairn Pynt.

Bengaard's (1995) 'boundary granite suite' comprises pale weathering, fairly homogenous garnet granitic gneisses, a variant of the widespread quartzo-feldspathic paragneisses or the garnet granulites of Sharp (1991). Many of the light-coloured rocks, interpreted photogeologically by Bengaard as marbles, are pale-weathering granites and leucogranites, or darker rocks covered by pale-coloured glacial drift. This applies to large tracts in south-western and southern Inglefield Land, shown by Bengaard (1995) as composing the southern part of the linear belt, and also areas to the south as far as the Inland Ice.

Other discoveries made during the 1995 field work were that large areas of meta-igneous rocks and orthogneisses in central Inglefield Land, east and west of Minturn Elv, contain important basic, intermediate and syenitic components. They are reflected on the aeromagnetic map (Fig. 3) as a large positive anomaly interpreted to represent basic igneous bodies by Bengaard (1995). A post-tectonic porphyritic granite massif with relatively low magnetic response occurs adjacent to the Inland Ice, south of Kap Agassiz (Figs 2, 3). The latter can hardly be claimed as a discovery: Koch (1920) shows an intrusive mass in this area on his initial geological map (see also Koch, 1933, p. 13).

The rocks of the Etah meta-igneous complex often contain appreciable amounts of magnetite, and most of the regional magnetic anomalies seem to be attached to rocks of this complex (Fig. 3). The electromagnetic anomalies are largely connected to a unit of grey paragneisses with variable contents of garnet, biotite, graphite and pyrrhotite which cover large parts of central and northern Inglefield Land, and include some of the granitoid rocks of Bengaard (1995).

Mineralisation

Reconnaissance-type mineral exploration was carried out in Inglefield Land in the period 1969–1973 by Greenarctic Consortium and Internationalt Mineselskab A/S and again two decades later in 1991 and 1995 by RTZ Mining and Exploration Limited. This work concentrated on the investigation of conspicuous gossans caused by iron sulphides that occur in the crystalline basement rocks. Mineralised surface samples showed elevated trace amounts of gold and base metals: max. 207 ppb Au, 3767 ppm Cu, 2565 ppm Zn, 960 ppm Ni (Sharp, 1991).

The mineralisation sites investigated by the Survey in 1995 fall conveniently into two main groups: (1) sulphide mineralisation, characterised by pyrrhotite with minor pyrite and traces of chalcopyrite; and (2) oxide mineralisation dominated by magnetite. The two groups may be intermixed.

Sulphide mineralisation

Sulphide mineralisation is widespread in central and north-eastern Inglefield Land as revealed by impressive red and yellow gossans which often stretch over several kilometres (Fig. 4B). These gossans are formed by deep weathering of sulphides, typically hosted by graphitic grey gneisses, and clearly registered on the geophysical maps as electromagnetic anomalies. The sulphides are mainly disseminated, but massive lenses of metre size do occur. Gold and base metal contents so far recorded are relatively low (max. 36 ppb Au, 980 ppm Cu, 2935 ppm Zn and 276 ppm Ni in 23 samples). Scattered outcrops of similar sulphide mineralisation were also observed along the south-west Inglefield Land coast (max. 1134 ppb Au, 1014 ppm Cu, 124 ppm Zn and 386 ppm Ni in four samples). Furthermore, sulphide gossans in gneiss related to amphibolite occur in a NE-trending belt north of Septembersøerne. Parts of this belt are relatively rich in pyrite and show slightly elevated gold-base metal contents (max. 294 ppb Au, 4216 ppm Cu, 345 ppm Zn and 219 ppm Ni in six samples). The origin of the mineralisation is not obvious. The graphite of the host gneisses indicates a marine origin, perhaps as cherty, sulphidic iron formations, whereas the occurrence of rounded quartz grains in massive sulphides points towards a formation by sulphurisation of heavy mineral lenses in a clastic succession.

Minor sulphide mineralisation, revealed by malachite staining, occurs in gneisses at gneiss–marble contacts. At the best investigated locality, *c.* 9 km south-west of Kap Agassiz, such mineralisation was followed for over 300 m along strike. Two chip samples averaged 36 ppb Au and 2382 ppm Cu over 0.8 m, whereas four grab samples contained up to 1188 ppb Au and 1.3% Cu. Furthermore, scattered, disseminated sulphides have been observed in mafic–ultramafic rocks and in a few quartz veins of decimetre thickness. Sulphides hosted by a 5–10 m thick pelite unit of probable basal Cambrian age have been reported from Marshall Bugt by Coppard (1996).

Oxide mineralisation

Magnetite is widespread in the felsic, mafic and ultramafic rocks of the Etah meta-igneous complex. The most distinct magnetic anomaly on Inglefield Land, situated at Minturn Elv, was found to be related to lenses of magnetite hosted by amphibolitic and ultramafic rocks (Fig. 3). Up to 20 cm thick lenses of massive magnetite, with minor spinel and olivine, were observed in outcrop, and modelling of the airborne geophysical data suggests that they may reach thicknesses of 200–300 m in areas completely covered by overburden. Preliminary investigations of samples from outcrop and extensive, magnetite-rich boulder fields indicate contents of up to 0.26% V_2O_5 and 0.1% Ni (Appel *et al.*, 1995).

Concluding remarks

The field work provided for a regional reconnaissance and appraisal of the main lithologies of the Precambrian shield: a major step forward in compilation of map sheet 6 of the 1:500 000 map series, covering North-West Greenland. The geochemical survey has contributed to the systematic geochemical mapping of Greenland (Steenfelt, 1993).

Most of the abundant and distinct electromagnetic anomalies detected by the airborne geophysical survey stem from a graphitic and sulphidic gneiss unit, wherein no significant amounts of gold or base metals were detected. It

Fig. 4. A:Marble and calc-silicate rocks (pale) of the Etah Group invaded by granitic sheets and dykes (brown) of the Early Proterozoic Etah meta-igneous complex. South of Kap Agassiz, north-eastern Inglefield Land. Height of section about 200 m. B: Typical rust zone in central Inglefield Land seen from the air (helicopter shadow for scale).

should, however, be stressed that, because of the deep weathering and frequent extensive moraine cover of the anomalous sites, a serious check of their economic potential should involve detailed geochemistry, ground geophysics and drilling. Magmatic magnetite occurrences with a significant tonnage potential have been demonstrated around Minturn Elv.

Seen against the considerable speculation and interest that the photographically defined circular structures were volcanic pipes (Bengaard, 1995; Stemp & Thorning, 1995a; Minex 1995b), an origin as surficial features is disappointing (Coppard, 1996; Appel, this report). However, it is the correlation with Canadian geology and the known kimberlite occurrences there that pierce the Proterozoic – Lower Palaeozoic platform strata (not the Inglefield Land circular structures) that initially designated northern Greenland as a prospective kimberlite exploration target (Dawes, 1994). This potential remains.

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The puzzle of the circular features in Inglefield Land, North-West Greenland

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In 1994 The Geological Survey of Greenland (GGU) conducted an airborne geophysical survey of Inglefield Land, North-West Greenland, financed by the Government of Greenland, Minerals Office. During photogeological studies in connection with the survey well over 100 circular structures were identified in a belt stretching from the Inland Ice across central Inglefield Land to the coast (Fig. 1; Bengaard, 1995). The structures were also identified on video-recordings from the airborne geophysical programme. The circular structures are up to 80 m across, and conspicuous due to their generally dark colour which contrasts with surrounding areas (Fig. 2). Some are ring-shaped, with the dark material concentrated around the circumference of the circles, while others are dark-coloured across their entire area.

Prior to GGU's investigations, the circular structures on Inglefield Land had been identified during a reconnaissance photogeological interpretation (Sharp, 1991), but had not been checked on the ground. The more detailed information available on the video-recordings from 1994 triggered numerous discussions concerning the origin of the structures and a variety of explanations were speculated on. The structures were interpreted to represent volcanic pipes (Stemp & Thorning, 1995), and thus particularly interesting if they were kimberlite pipes. Other suggestions discussed in house at the time were meteoritic impacts or permafrost features such as pingos. The idea that the structures represented kimberlite pipes caused several mining companies to apply for concessions in Inglefield Land. One company which had obtained a concession in the area carried out field work during June 1995, with the author as a participant. In July and August the Geological Survey of Denmark and Greenland (GEUS) carried out field work in the area, again with the author as a participant. During this field work a glacial origin of the circular structures was proved most likely (Appel, 1996)

Central Inglefield Land is a peneplain consisting of Precambrian gneisses and supracrustal rocks intruded by granites and syenites, and overlain by upper Proterozoic and Cambrian sediments. The surface of the peneplain is dominated by large boulder fields with scattered outcrops. The circular structures, named Minturn circles after the river Minturn Elv (Appel, 1996), occur in a fan-shaped belt about 40 km long and up to 25 km wide (Fig. 1), and are most abundant in the southern part of the belt. More than 300 circles and rings have been observed, of which about 175 have been investigated on the ground.

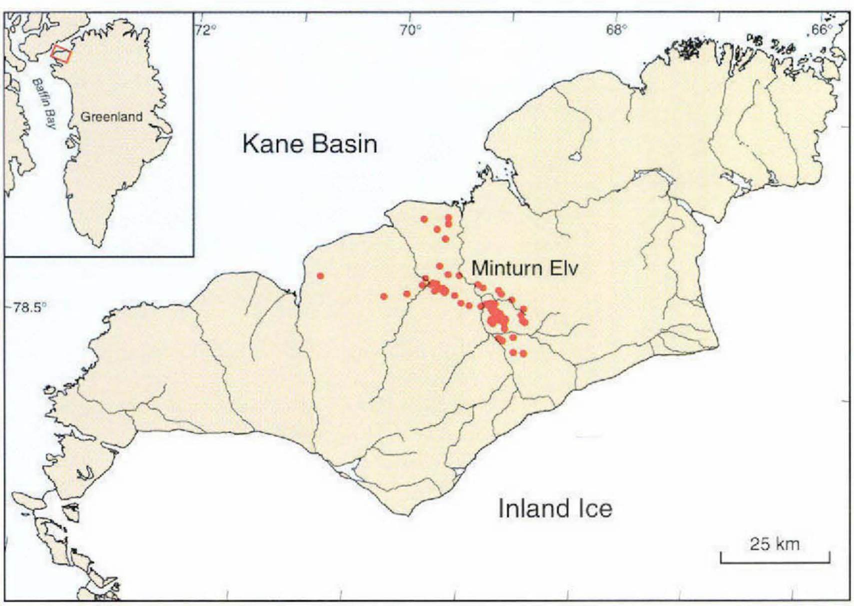

Fig. 1. Fan-shaped area with circular structures across central Inglefield Land. Only circular structures close to the border of the fan-shaped area are indicated. Thus in the central part, numerous circles and rings occur which are not shown on the map.

Fig. 2. Minturn circles including ring-shaped examples on boulder field of Precambrian gneisses in central Inglefield Land. Many of them have been disturbed by frost-boils. The largest circle is about 50 m across. Aerial photograph.

The Minturn circles range in size from a few metres to about 80 m. The width of the rings in the ring-shaped type varies from a few metres to about 8 m. The dark rings and circles consist of angular to slightly rounded boulders, cobbles and pebbles of syenite mostly covered by black lichens, which contrast strongly with the light coloured Precambrian gneisses and Cambrian sediments (Fig. 2).

The circular structures are at the same level as the surrounding boulder fields and outcrops. The syenite boulders occur as thin sheets, often just one layer thick, which as carpets drape the boulder fields and outcrops of Precambrian gneisses and Proterozoic to Cambrian sediments on which they occur. These carpets are not only found on flat surfaces but also on slopes.

The field relationships clearly show that the Minturn circles are not volcanic pipes, nor are they permafrost features. They cannot have been deposited by running water, and it is therefore concluded that they were deposited from an extension of the Inland Ice.

The first stage in the formation of the circular structures is thought to take place within so-called cold ice (which means the the ice margin is frozen to the ground due to permafrost) by a melting/refreezing process similar to that described by Boulton (1970, 1972) and Weertman (1971). In Inglefield Land this process took place over a large syenite complex in south central Inglefield Land where ice wedges with syenite debris were formed and subsequently transported towards the north. During melting of the ice cover, the debris became exposed on the surface of the ice sheet and subsequently concentrated in evolving meanders of stream systems developed on the flat, stagnant Inland Ice. When the ice finally melted the ring-shaped and circular accumulations were gently deposited on the flat plains of Inglefield Land.

Circular deposits as found in central Inglefield Land are probably quite common in the high arctic. They are, however, mostly invisible, as the surrounding rock types tend to have the same compositions as the circular deposits.

In the 1950s comparable circular structures were spotted from the air in North-East Greenland. Follow-up field work on the ground was not possible at that time, and they were provisionally interpreted as impact structures (Ellitsgaard-Rasmussen, 1954). Observations on the ground by GGU geologists H. F. Jepsen and F. Kalsbeek in 1979, and in 1995 by T. Tukiainen and M. Lind showed these circles to consist of dark basalt blocks deposited on light coloured sediments, closely resembling in appearance and probably also in origin the Minturn circles of Inglefield Land.

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Airborne geophysical surveys in 1995

Leif Thorning and Robert W. Stemp

Two major airborne geophysical surveys were carried out during 1995, the second year of a planned five-year electromagnetic and magnetic survey programme (project AEM Greenland 1994–1998) financed by the Government of Greenland, and the first year of an aeromagnetic survey programme (project AEROMAG 1995–1996) jointly financed by the governments of Denmark and Greenland; both projects are managed by the Geological Survey of Denmark and Greenland (GEUS). The budget for each of the surveys is in the order of one million US dollars per year. The two 1995 survey areas are shown in Fig. 1, where the AEM Greenland 1994 survey area (Stemp & Thorning, 1995a, b) and the surveys planned for 1996 are also shown. Summary information concerning the two 1995 surveys is listed in Table 1.

The date of public release of data is 1 March 1996 for both surveys, in accordance with the primary objective to stimulate commercial mineral exploration in Greenland by making the data quickly available to the mining industry. The data acquired are included in geoscientific databases at GEUS for public use; digital data and maps may be purchased from the Survey. The main results from the 1995 surveys are published in Stemp (1996) and Thorning & Stemp (1996).

Project AEM Greenland 1995: Maniitsoq – Nuuk, southern West Greenland

The main objective of this survey was to investigate the 'norite belt' in the Maniitsoq – Nuuk area, which is known for its occurrences of disseminated sulphides and where kimberlite dykes have been observed. The survey was flown between 15 July and 11 September 1995 by Geoterrex Ltd (Canada) using a CASA aircraft with geophysical equipment. Cominco Ltd holds extensive mineral exploration licences in the area, and provided a financial contribution towards the survey. Cominco staff also provided valuable pre-survey technical assistance and had full access to the data in the field; however, Cominco has no special rights to the data after the general release date.

Survey equipment and technical specifications were similar to those used for the first survey of the AEM Greenland project over Inglefield Land in 1994 (Stemp & Thorning, 1995a, b) with two major exceptions: survey line spacing was reduced from 400 m to 200 m over the central part of the survey area, where norite occurrences are especially numerous, resulting in more detailed maps at scale 1 : 20 000 of this part of the survey area; and a *z*-axis GEOTEM receiver coil was added to provide potentially greater depth of exploration and improved anomaly source discrimination.

Survey operations were based at Nuuk airport, where hangar facilities were available; the international airport Kangerlussuaq (Søndre Strømfjord), was used as a refuel-

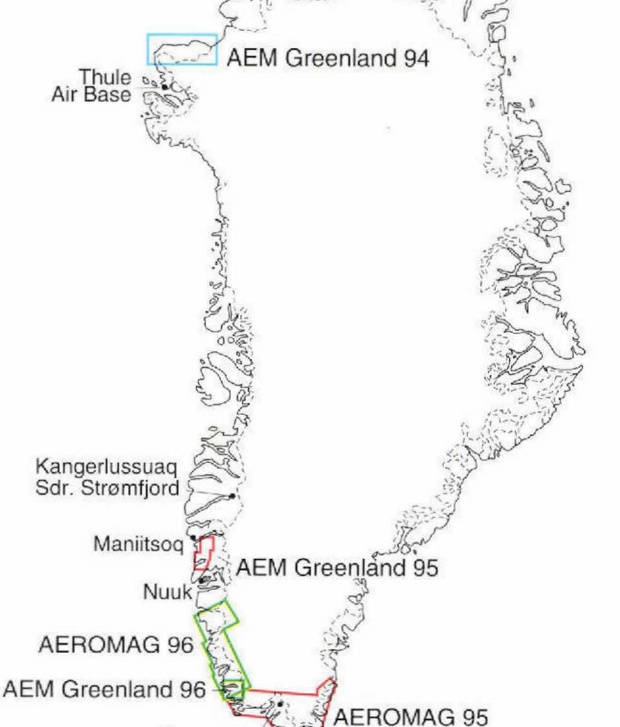

Fig 1. Index map showing the three surveys already flown in projects AEM Greenland 1994–1998 and AEROMAG 1995–1996 and the two surveys planned for 1996.

ling base on some days with two flights. The field processing was undertaken in Nuuk.

Compared with the 1994 survey over Inglefield Land flown from Thule Air Base, average production per hour and per day was significantly higher in 1995, primarily due to the much shorter ferry distance to the survey area, and despite the fact that more days were lost due to bad weather in 1995.

As anticipated in the planning of the survey, the rough terrain was a serious problem for fixed-wing surveying in parts of the Maniitsoq – Nuuk region. This necessitated some compromise in selecting survey boundaries and flight line direction. However, the AEM Greenland 1995 survey resulted in the successful acquisition of more than 20 000 line km of high sensitivity, airborne electromagnetic and magnetic data, including some reconnaissance lines flown south and east of the survey area. The average sampling distance along lines was 7–10 m, which combined with the close line spacing provides a very detailed data set revealing a wealth of geological information. Results of the project in the form of digital data, maps, processing report and preliminary interpretation report are now available from the Survey (Stemp, 1996).

Project AEROMAG 1995: South Greenland

This extensive and ambitious, high sensitivity airborne magnetic survey of South Greenland was carried out in order to map regional geological structures throughout the region, especially under the Inland Ice, and to gain a better understanding of the complex geology of the area.

The programme was extremely challenging for a number of reasons. The obstacles for airborne surveying that had to be overcome included some of the most severe terrain in Greenland, ranging in elevation from sea level to over 2000 m, with extensive areas covered by either the Inland Ice or by sea water with uncertain depths to underlying bedrock surfaces.

The project was flown by Sander Geophysics Ltd (Canada) during approximately seven months of surveying, which started on 13 August 1995, almost three months later than originally planned. The base was at Narsarsuaq airport, where hangar facilities were made available. As Narsarsuaq is the only suitable airport in the area, extra safety measures had to be undertaken, as the region is known both for its notorious and unpredictable bad weather and turbulence generated by the Inland Ice and local ice caps.

Table 1. Summary information for the two 1995 geophysical surveys

Project:	AEM Greenland 1995	AEROMAG 1995
Objectives:	Detailed geophysical mapping	Regional geophysical mapping
	Detailed geological mapping	Regional geological mapping
	Detection of massive sulphides	Relate east and west coasts of South Greenland
	Detection of kimberlite pipes	
Size:	20 500 line km	89 500 line km
Flight line spacing:	200 or 400 m	500 m
Tie line spacing:	4 km	5 km
Survey altitude:	120 m terrain clearance	300 m drape
Contractor:	Geoterrex Ltd, Canada	Sander Geophysics Ltd, Canada
Base of operation:	Nuuk	Narsarsuaq
Geophysical sensors:	GEOTEM electromagnetics	Caesium magnetometer
	Caesium magnetometer	
Navigation:	Differential GPS	Differential GPS
Aircraft:	one CASA	one Cessna 402
		one Beachcraft Queenair
Survey dates:	15 July 95 – 11 Sept 95	13 Aug 95 – 15 Feb 96
Production/aircraft day:	345 line km	455 line km
Total cost:	DKK 6.0 mill.	DKK 5.5 mill.
Cost/line km:	DKK 270	DKK 60
Financing government:	Greenland	Greenland / Denmark

Table 2. Productivity data for AEROMAG 1995

Month	Aircraft days	km flown	km/ aircraft days
Aug	19	7 201	379
Sep	40	10 622	266
Oct	55	41 688	758
Nov	30	7 592	253
Dec	12	3 723	310
Jan	21	4 292	204
Feb	37	9 184	248
Mar	15	5 453	364

A further complication was the limited daylight hours in late autumn and winter, and the fact that geomagnetic activity is usually high in the region. These difficulties are reflected in the strongly varying productivity figures listed in Table 2.

Two specially equipped twin-engine aircraft were used, although not continuously, to complete the programme of approximately 90 000 line km. A computer assisted drape flying programme, designed and tested during this survey by Sander Geophysics Ltd, was used for the first time during this project. It enabled the flight crews to maintain an optimal drape position at all times, thus minimising problems usually associated with terrain clearance in mountainous regions, and producing both a better and a safer survey. The method is based on a digital elevation model which combines terrain data for the region with slopes adjusted to the optimal rate of climb and descent of the aircraft used for the survey. The aircraft autopilot uses this model to position the aircraft on the optimal drape surface, ensuring better continuity both along and across survey flight lines.

Data from the AEROMAG 1995 project will be compiled at scale 1:50 000 (42 map sheets) and at 1:250 000 (2 map sheets). The Survey report discussing the results is expected to be available in mid-1996.

Acknowledgements: The staff of both Geoterrex Ltd and Sander Geophysics Ltd are acknowledged for their dedicated approach to the successful completion of both projects. The Government of Greenland, Minerals Office, gave valuable assistance to Geoterrex Ltd in Nuuk and to the Survey personnel supervising the operations. Airport authorities, agencies and companies at the three airports involved are thanked for their assistance to the crews from Geoterrex Ltd and Sander Geophysics Ltd.

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Use of gas analyses in modelling mineralising events in the Jameson Land Basin, East Greenland

Mikael Pedersen

Jameson Land has attracted much attention during the past century because of its potential with respect to both minerals and oil occurrences. Extensive geological investigations in particular by Lauge Koch's expeditions, Nordisk Mineselskab A/S, Atlantic Richfield Company (ARCO) and the Geological Survey of Greenland (GGU) have resulted in finds of numerous mineral occurrences and in a thorough understanding of the geological framework of the region. The Blyklippen Pb-Zn occurrence in the Mesters Vig area (Fig. 1) is the only ore deposit that has so far been exploited; other important ore mineral concentrations include the Malmbjerget porphyry Mo deposit, the Karstryggen Sr deposit and extensive sediment-hosted Pb, Zn, Ba and Cu mineralisation within the region.

Until now the latter have been relatively poorly known, and in order to expand knowledge of these potentially important mineral deposits a Ph.D. project was initiated at the Survey in 1993 with support from the Danish Research Councils. The aim of the project is to increase understanding of the mineralising events with the help of lead isotope studies and various fluid inclusion analysis techniques, which will help to evaluate the mineral potential of the unexposed parts of the basin.

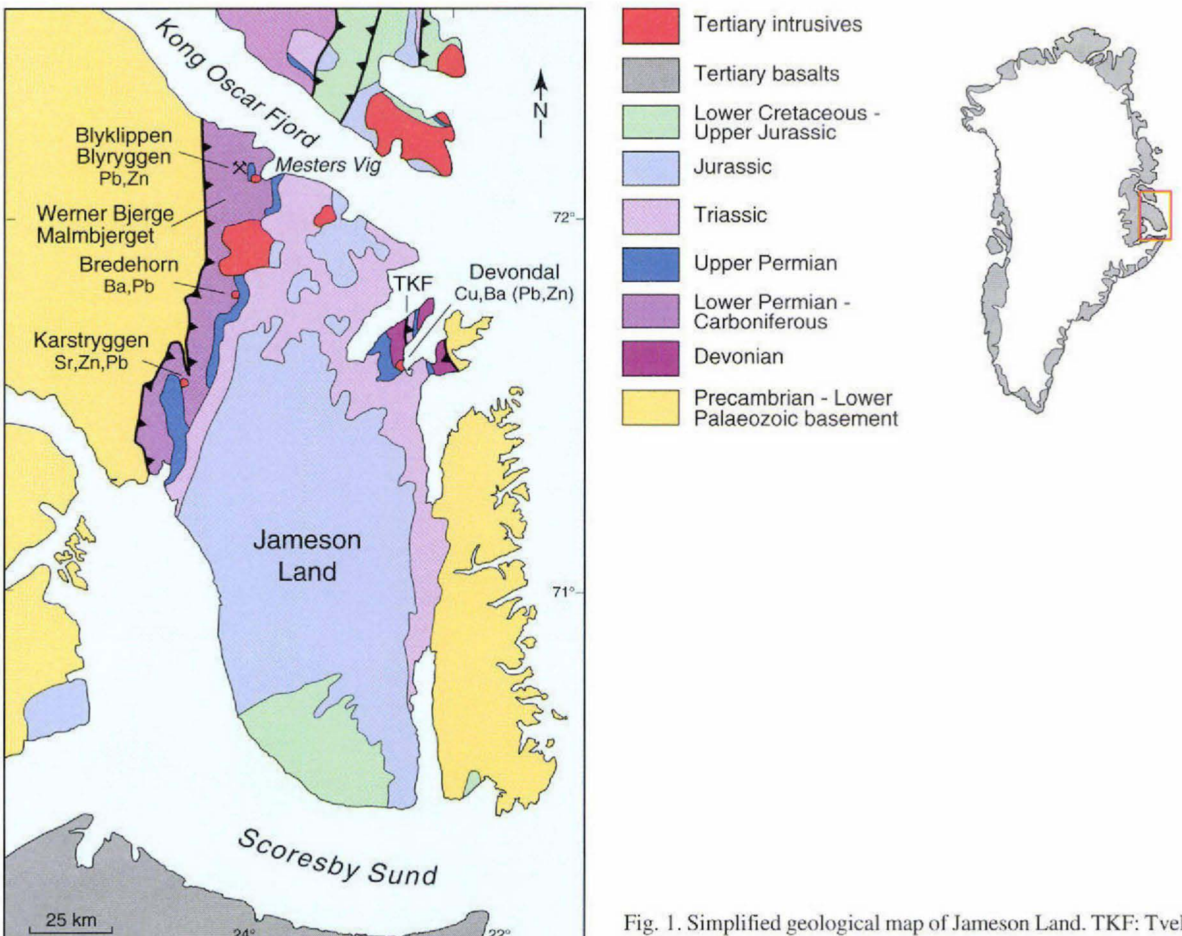

Fig. 1. Simplified geological map of Jameson Land. TKF: Tvekegledal fault.

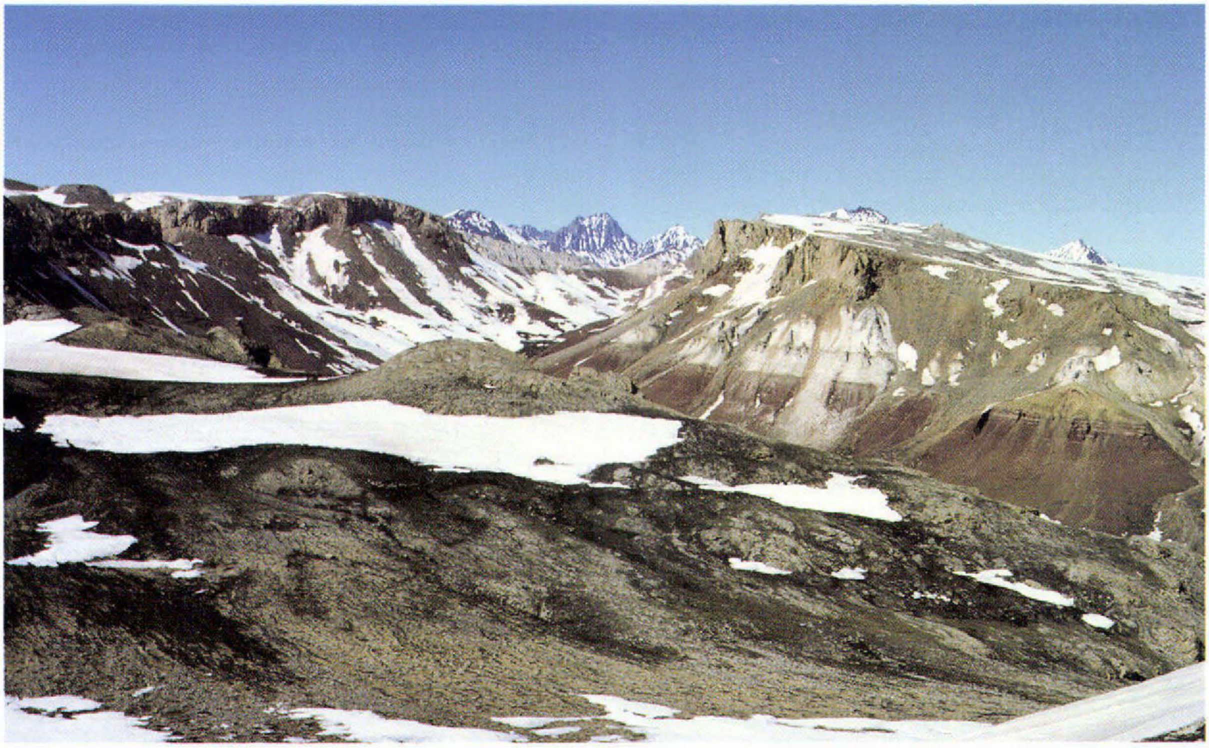

Fig. 2. View north-west over Revdal from Karstryggen. Red units are Upper Permian conglomerate (Huledal Formation), bright white units are Upper Permian gypsum lenses, and uppermost grey units are Upper Permian carbonates (Karstryggen and Wegener Halvø Formations) where the Zn-Pb mineralisation is located.

Geological overview

The Jameson Land Basin (Fig. 1) forms the southern part of a *c.* 700 km long N–S series of sedimentary basins extending throughout the outer coastal areas of North-East and East Greenland. Basin formation was initiated in the Middle Devonian in response to extensional collapse of the over-thickened Caledonian crust (Larsen & Bengaard, 1991). The total sedimentary sequence in the Jameson Land Basin reaches a thickness of 16–18 km at the basin centre (Larsen & Marcussen, 1992). Continental sedimentation in the Devonian – Lower Permian was succeeded by marine sedimentation in the Upper Permian and deposition of alternating marine and continental deposits from the Triassic until the Upper Cretaceous. The whole area was covered by up to 2 km of Tertiary flood basalts during the initial opening of the North Atlantic Ocean in the Paleocene, and alkaline intrusions were emplaced in the northern part of the area later in the Tertiary (Larsen & Marcussen, 1992; Brooks *et al.*, this report).

Occurrences of Pb, Zn, Ba and Cu are concentrated in the upper parts of the 12 km thick succession of Devonian to Lower Permian continental clastic sediments and in the overlying Upper Permian transgressive succession (Foldvik Creek Group). In the eastern parts of the basin Triassic deposits are also mineralised, but no mineralisation has so far been reported in younger parts of the sedimentary sequence (Harpøth *et al.*, 1986).

Mineralisation

The project has been concentrated around four areas with different types of mineral deposits (Fig. 1):

- Fine-grained sphalerite and galena in karst-breccias in the Foldvik Creek Group at Karstryggen (Fig. 2).
- Replacement barite with associated galena in the Foldvik Creek Group at Bredehorn.
- Fault related vein-type Pb and Zn (± Cu and Ba) in Upper Carboniferous to Lower Permian clastic sediments at Blyryggen.
- Cu- and Ba-veining in the upper parts of carbonate build-ups in the Foldvik Creek Group at Devondal.

These areas were visited in the summer of 1994, when systematic sampling of minerals and rocks was carried out with special reference to the different kinds of analytical work involved in the project.

Gas analysis

Analyses of gases in inclusion fluids were undertaken at New Mexico Tech, Socorro, USA under the supervision of Prof. D. Norman, following the methods of Norman & Sawkins (1987). Gases were extracted from the samples either by crushing or thermal decrepitation, and were analysed using a quadropole mass spectrometer.

The crushing method is quick and relatively inexpensive but allows only a small amount of gas to be measured, resulting in major uncertainties.

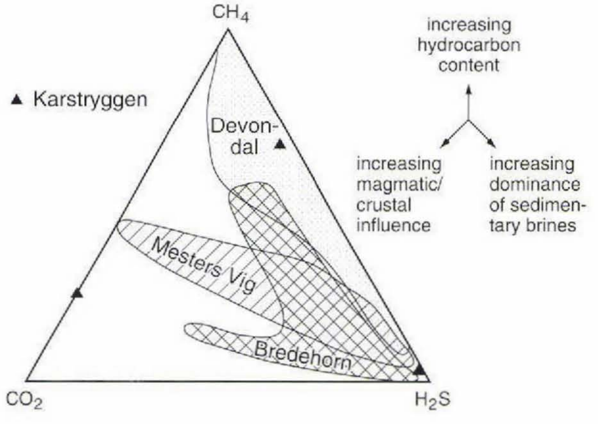

Fig. 3. Ternary plot showing the characteristics of fluid inclusion gases from Jameson Land Basin.

Thermal decrepitation has the advantage that large amounts of gas are released, and can be trapped and fractionated, allowing each fraction to be analysed separately. This is a far more precise technique; however, not all thermal effects that take place during heating can be predicted and corrected for.

In this study, quartz was most frequently used, but sphalerite, barite, fluorite, calcite and celestite were also analysed when present as sufficiently large grains. Both crushing and thermal decrepitation were undertaken, often both methods on the same sample. For statistical purposes, the values from the crushing experiments are the most usable, as more than 350 analyses have been carried out on more than 50 samples.

The gas data show that different types of fluids have been involved in ore formation (Fig. 3). Samples from Bredehorn and Blyryggen, both located near the western fault-bounded basin margin, show the influence of two fluids: a hot (> 250°C) component with relatively low salinity and high in CO_2, and a cooler (130–150°C) fluid with higher salinity and lower CO_2 content. The hot fluid is interpreted as being a deep crustal fluid that has been mobilised by the intrusion of the alkaline Werner Bjerge complex, while the cooler fluid is considered to be a local sedimentary brine. The role of the Werner Bjerge complex in the generation of the hot fluid is indicated at Blyryggen, where the gas data show a trend towards higher temperatures, lower salinities and higher CO_2/N_2 ratios the closer the samples were taken to the intrusive complex. At Bredehorn, samples in general show higher CO_2/N_2 ratios than at Blyryggen, which is consistent with their position closer to the Werner Bjerge. The two-component mixing at Bredehorn and Blyryggen shown by the fluid inclusion data has also been demonstrated by lead isotope data, which suggests that lead from two different sources is present (Jensen, 1993).

The presence of two fluids with different gas components is also seen in Devondal at the eastern basin margin. One of the components is similar to the low temperature component at Blyryggen, and is interpreted as a sedimentary brine, while the other is very rich in hydrocarbons. There seems to be a geographical pattern with H_2S/CH_4 ratios increasing eastwards towards the vicinity of the Tvekegledal fault. This might indicate an increased dominance of sedimentary brine component in that direction. The hydrocarbon-rich nature of samples from the west end of Devondal can be explained by the presence of pure hydrocarbon inclusions.

According to Stemmerik (1991) liquid hydrocarbons entered the Upper Permian carbonate buildups in the Late

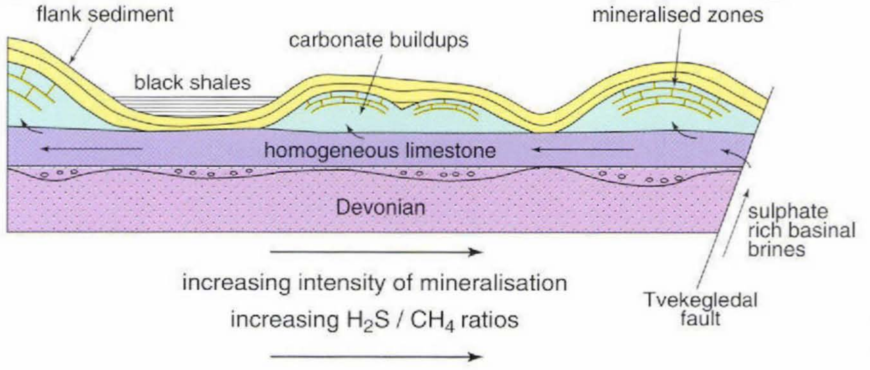

Fig. 4. Simplified model for the formation of the Devondal occurrences.

Cretaceous, but were flushed out by ore-forming fluids in the Tertiary. The gas analyses show no evidence of CO_2-enrichment, which is seen in areas where magmatic activity has clearly played a role in ore deposition, suggesting that the mineralising fluids in Devondal are heated sedimentary brines. This is consistent with the lead isotopes that suggest a local source for the lead. Thus a model for the mineralising event in the area envisages sedimentary brines, probably enriched in SO_4^{2-} and base metals, to be mobilised by a thermal event in the Tertiary and introduced to the Devondal area along the Tvekegledal fault. The fluids then migrated laterally from the fault zone through permeable layers and some entered the overlying carbonate build-ups, where hydrocarbons were already trapped (Fig. 4). The meeting between hydrocarbons and sulphate bearing brines resulted in thermochemical sulphate reduction and precipitation of sulphide minerals. The barite and quartz veining which is widespread in the area was probably formed by precipitation from cooling sedimentary brines.

At Karstryggen no suitable minerals for gas analysis were found associated with the Pb and Zn occurrences. However, some fine-grained sphalerite separated from a Zn-rich sample, celestite from the nearby Sr-deposit and cavity-filling calcite found in the area, were analysed. Due to the fragility of all these minerals, air-contamination was a problem during the analyses, which means that N_2 and Ar values are unreliable.

Analytical results from Karstryggen, however, suggest that the Zn-Pb mineralisation has a gas component either derived from a magmatic or deeper crustal source, because of enrichment in CO_2; the celestite and calcite show no such component. It is suggested that the Zn-Pb occurrence was formed in close association with Tertiary lamprophyric dykes which are seen to intrude the clastic sediments below the ore zone. The celestite mineralisation, on the other hand, is related to another and probably earlier event (Scholle *et al.*, 1990).

Future work

Further investigations on the mineral potential of the region are planned, with new fieldwork in 1996 (Stemmerik *et al.*, this report).

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Glacier and climate research on Hans Tausen Iskappe, North Greenland – 1995 glacier basin activities and preliminary results

Henrik Højmark Thomsen, Niels Reeh, Ole B. Olesen and Peter Jonsson

A glaciological project was carried out between 1993 and 1995 on Hans Tausen Iskappe, a local ice cap in central North Greenland (Fig. 1). The project is funded by the Nordic Environmental Research Programme 1993–1997 launched by the Nordic Council of Ministers and by the European Union's third Framework Programme ENVIRONMENT, and is a collaboration between six institutions from Denmark, Iceland, Norway and Sweden.

The main goals of the project were to investigate the present and past climate and glacier dynamics of North Greenland by means of ice-core records, ice margin studies, mass balance and climate studies and glacial geological studies on and around Hans Tausen Iskappe. This ice cap was chosen for the following reasons: (1) Only very limited palaeoclimatic ice core data exist for North Greenland. (2) North Greenland is considered to be a region of high climatic variability and sensitivity, as indicated by Quaternary geological data and predicted by coupled atmosphere-ocean general circulation models (GCMs) (Funder *et al.,* 1984; Bretherton *et al.,* 1990).

The three years of work have mainly comprised field activities, with planning and reconnaissance in 1993 and an increasing level of field activities during the summers of 1994 and 1995. The activities can be divided into two main parts: ice core drilling and glacier basin investigations. Since most data and material were obtained during the 1995 field season, only preliminary analyses and data processing have so far been undertaken. This contribution deals mainly with the glacier basin activities during the summer of 1995; other activities are only briefly described.

Hans Tausen Iskappe and locations of activities

Hans Tausen Iskappe is a local ice cap, about 75 km from north to south and 50 km from east to west, located in western Peary Land (Fig. 1). The ice cap has several domes (outflow centres) which reach elevations of 1200 to 1300 m a.s.l. Several outflow glaciers drain the ice cap to the west, north and east, often terminating at elevations of a few hundred metres; some reach sea level with a calving front. The southern margin of the ice cap can be characterised as a 'quiet' sector, often covered by snow drifts which survive the summer melt period.

Field work was mainly undertaken at two localities: (1) the southern dome; and (2) an outlet glacier basin including a dome in the north-east part of the ice cap (Fig. 1). The main activity in the southern dome region was ice core drilling to bedrock with associated measurements of ice thickness, strain-rate and velocity. The work in the outlet glacier basin constituted glacier-climate and mass balance studies, collection of ice and snow samples from the surface, and measurements of ice thickness, ice velocity and englacial temperatures. In addition glacial geological investigations were made in Nordpasset and at Adolf Jensen Fjord, north and west of the ice cap, respectively (Fig. 1).

Field activities 1993

A survey of surface and bedrock elevations was made in 1993 over the entire ice cap by radio-echo sounding from a Twin-Otter aircraft to identify a suitable general area for the deep drilling (Hammer, 1995). In addition, reconnaissance flights were made to locate suitable sites for the glacier basin investigations.

Field activities 1994

Ice core drilling activities

Detailed surface and bedrock elevations were measured from the ice surface within a 6 × 6 km area centred on the intended drill site on the southern dome, using radio-echo soundings and kinematic GPS-positioning (Fig. 1). In addition, similar data were collected along two profiles, 16 km to the south-west and 6 km to the north of the drill site. A strain net was established and measured by GPS, and a 6 m ice core drilled for $\delta^{18}O$ analysis (Hammer, 1995).

Glacier basin activities

A stake network for mass balance measurements and study of surface-ice velocity and deformation was established in the outlet glacier basin at the north-east part of the ice cap (Figs 1 & 2). The stakes were measured and positioned by GPS several times during the field season. Snow pit samples and firn cores were obtained from the

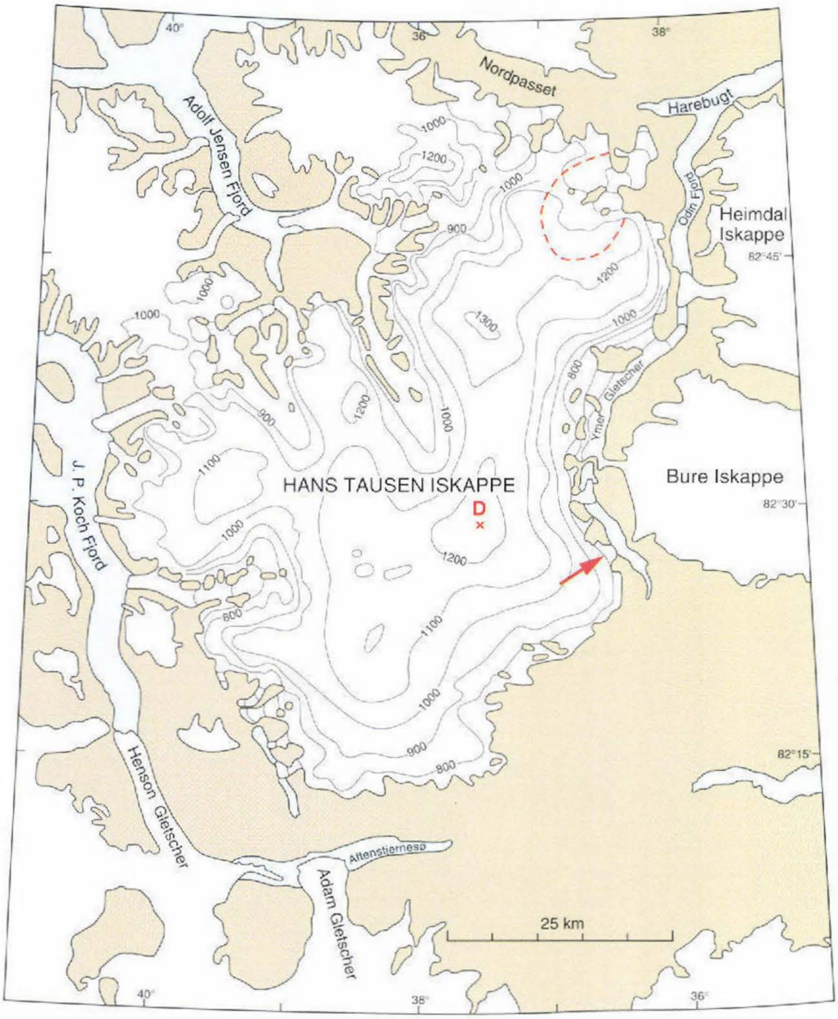

Fig. 1. Hans Tausen Iskappe. Map based on data from the National Survey and Cadastre, the Geological Survey of Denmark and Greenland and the Geophysical Department of the University of Copenhagen. D: Site of ice core drilling. Red dotted line: Limit of ice cap sector for glacier basin investigations. Enlarged map of this sector shown in Fig. 2. Red arrow: Location of surface ice sampling at an outlet glacier south-east of the southern dome.

accumulation area of the basin, as well as measurements of englacial surface temperatures to a depth of 10 m at selected stakes.

Daily measurements of ablation in a 10-stake cluster were made together with logging of radiation components, ice albedo and simple climate data, including air temperature, humidity and wind speed (Braithwaite *et al.*, 1995).

Surface-ice samples for $\delta^{18}O$ analysis were collected in the ablation area, and samples of snow and firn from the accumulation area.

Lastly, glacial geological studies were carried out along the northern margin of Hans Tausen Iskappe with the aim of providing information about Holocene and earlier variations in ice cap extent (Landvik & Hansen, 1994).

Ice core drilling activities 1995

In 1995 ice core drilling was made on the southern dome from the surface to bedrock and a 345 m long ice core of excellent quality was retrieved. In addition, an extra shallow core was drilled to a depth of 38 m, and a pit was dug to obtain *in situ* samples for chemical studies in the porous upper metres of the ice cap (Hammer, 1995).

Glacier basin activities 1995

Logistics

Field work was carried out in two periods, in June and in August. In June equipment and personnel were transported to and from Hans Tausen Iskappe from Station Nord with a ski-equipped Twin-Otter aircraft. A base camp was established at the eastern margin of the outlet glacier (Fig. 1). Due to favourable snow conditions, except on the lowermost part of the glacier tongue where slush fields were developing, moving about in the area was generally easy using snow scooters.

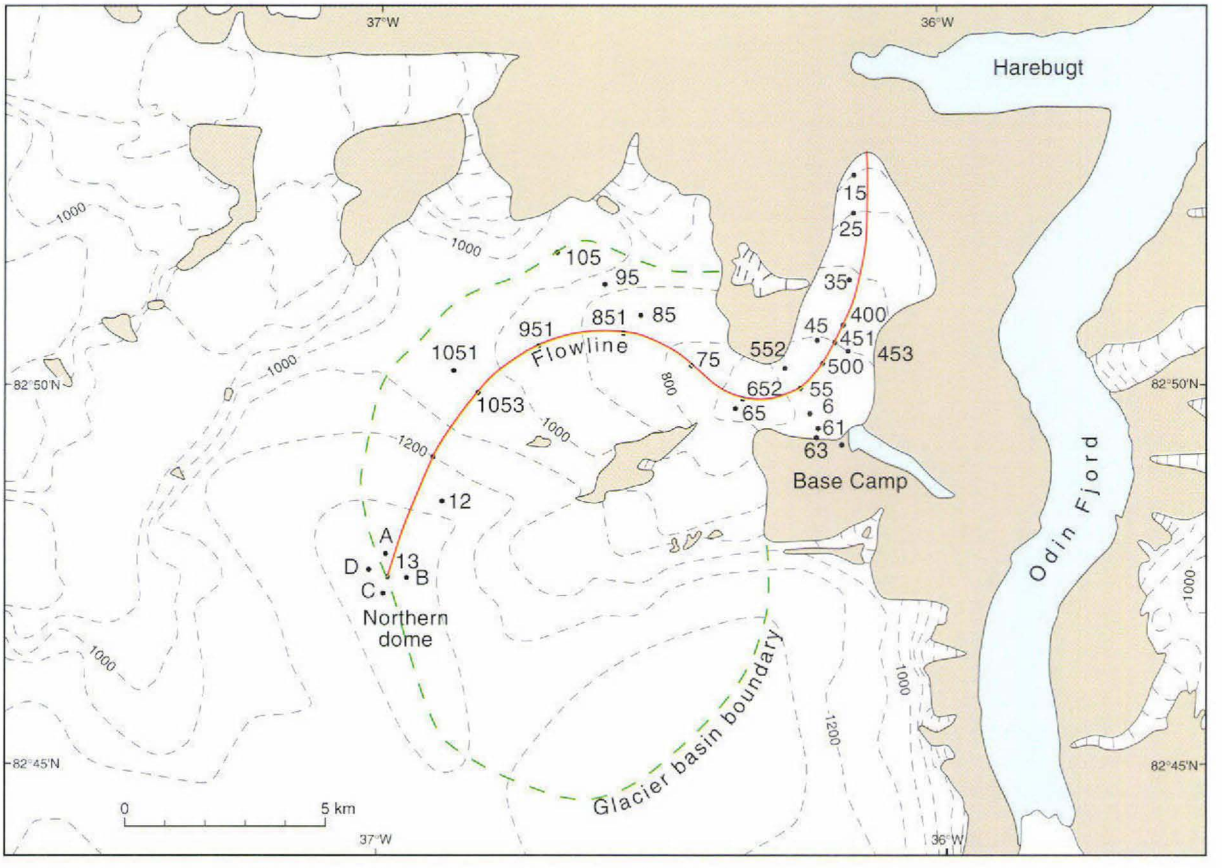

Fig. 2. North-eastern part of Hans Tausen Iskappe showing ice cap sector for glacier basin investigations (see also Fig. 1). Stakes for mass balance and ice velocity measurements are shown, as well as the central ice flow line from the northern dome to the glacier terminus.

In August equipment and personnel were transported to and from Hans Tausen Iskappe from a Survey base camp located at Centrum Sø in Kronprins Christian Land, eastern North Greenland, with a combined helicopter and Twin-Otter operation. Traffic on the ice cap in August was difficult due to the development of extensive deep slush fields, but helicopter support was only needed on one occasion.

Ice-thickness measurements

Ice-thickness measurements by radio-echo soundings were made in June, and covered the entire glacier basin (Fig. 2) using snow scooters to drag the radar system. The data will serve as input for ice flow modelling. The system used consists of a control and logging module, a generator, two antennae (80 MHz high power transmitter and receiver) and connecting cables mounted on light-weight sledges (Jonsson, 1994).

A total of 70 line km of data were collected, including a 15 km long profile following the central flow line from the ice tongue to the northern dome (Fig. 2) and two profiles parallel to the central flow line but approximately 1 km to each side. In addition, several profiles perpendicular to the central flow line were made, together with a dense net of lines on the northern dome (Jonsson, 1995). Navigation was by low-resolution hand-held GPS receivers, with a more accurate tracking made by continuous kinematic GPS positioning. All data from the radio-echo survey were recorded in the field as graphic output on a line scan recorder and on cassette tapes. The data awaits further processing in combination with the GPS data. However, a comparison of ice-thickness data from the radio-echo sounding and hot water drilling around stake 451 (see below) shows that good quality data can be expected. Maximum ice-thicknesses of up to 350 m occur in the glacier basin, whereas the ice-thicknesses along the centre line of the glacier tongue range between 250 m and 300 m; ice-thickness at the northern dome is about 250 m.

Hot water drilling for ice temperature measurements

In order to measure englacial temperatures from the ice surface to the bottom of the ice it was planned to install

Fig. 3. Hot water drilling for installing thermistor string at stake 451 on Hans Tausen Iskappe.

thermistor strings at the two strain-net sites at stake 13 on the northern dome, at stake 451 on the glacier tongue and around the equilibrium line near stake 75 (Fig. 2). The englacial temperature data will serve as input for ice flow model studies. The holes were drilled with a hot water drill developed at the Survey (Olesen, 1989) and used in connection with glacier-hydrological studies on the Greenland ice sheet (Thomsen *et al.,* 1989). However, due to very unfavourable drilling conditions only the thermistor string at stake 451 was successfully installed, reaching bedrock at a depth of 288 m below the ice surface (Fig. 3).

Temperature readings were made several times in the drill hole at stake 451 from 3 to 19 August. Similar temperature readings in hot water drill holes on White Glacier, Axel Heiberg Island, Canada (Blatter, 1985), showed that the temperatures are close to equilibrium state after 2 to 3 weeks, and the last readings at stake 451 on Hans Tausen Iskappe (on 19 August) are therefore assumed to be close to equilibrium (Fig. 4). The englacial temperature varies between −18.5°C at 10 m depth to about −1.5°C at the bottom. The relatively high temperature at the bottom was unexpected, but indicates that even a moderate climatic warming at the surface might bring the basal temperature in the marginal zone to the pressure melting point and result in increased ice flow velocities.

The planned drilling at stake 75 was abandoned due to the development of extensive deep slush fields at elevations higher than 700 m a.s.l. It was therefore decided to drill at stake 652 just below the stake 75 location where it was possible to move on the ice surface. The drilling went smoothly to a depth of about 120 m, when the penetration of the drill slowed down, and at 220 m drilling was abandoned. These difficulties with the drilling are assumed to be due to the presence of rock debris layers in the ice, as stake 652 is located downflow of a large nunatak located in the central part of the ice cap sector (Fig. 2); a medial moraine can be followed on the ice surface down-glacier from the nunatak. Two further attempts to drill at a location between stake 652 and 75 and between stake 55 and stake 6 were abandoned for the same reason.

The drilling operation on the northern dome at stake 13 started on 14 August but had to be abandoned due to breakdown of equipment.

Mass balance 1994/1995

The stakes established in June 1994 between the northern dome at an elevation of about 1320 m and the terminus of the outlet glacier tongue at an elevation of about 220 m were visited on several occasions in June and August 1995, to measure the transit balance for the winter period 1994/95 and the summer period 1995, respectively. Ablation readings and snow soundings were made. In the accumulation area stake readings were made to record snow accumulation and melt. In addition, density profiles were made in the top few metres of the snow and firn in June and August to compare the profiles and detect the effects of summer melting and refreezing. Snow and firn samples for $\delta^{18}O$ analysis were selected to investigate possible fractionation in the accumulation area in connection with refreezing and formation of superimposed ice. The snow and firn densities were measured in June and August to a reference level of 2 m depth, which was assumed to be below the depth of maximum percolation; experience from the Devon Island ice cap in Arctic Canada has shown that the depth of maximum percolation there is less than 2 m (Koerner, 1970). The density measurements were made in snow pits and samples were taken from the walls of the pit. Samples below

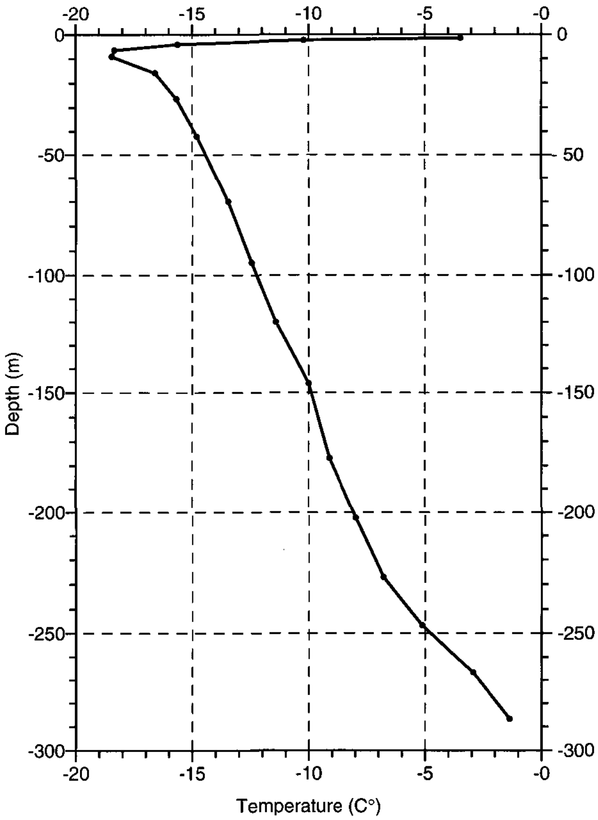

Fig. 4. Temperature–depth profile on the glacier tongue at stake 451. The glacier bottom is at a depth of 288 m.

the snow pit were taken using a SIPRE corer.

Mass change measurements in the accumulation area show that all melting refreezes in the snow and firn, together with any small amounts of summer precipitation. The exact values of the area mass change are uncertain, because the measurements only represent one point at each location. However, the general trend for all measured locations in the accumulation area shows that the transient balance for the summer period is close to zero. The mass balance study also showed that slush, several decimetres thick, develops late in the melt season over extensive areas of the glacier basin. Measurements indicate that most slush refreezes to form ice layers in the snow and firn or superimposed ice. This process releases energy (latent heat) causing local warming of the surface-near layers of the glacier, which is confirmed by measurements of ice temperatures in the top 10 m of the glacier at several locations.

To explain the melting and refreezing processes, further work is needed, including modelling of the temperature in the snow and firn based on the recorded near surface temperature data. This also includes the analysis of snow and firn $\delta^{18}O$ values to study possible seep-away of summer snow with high $\delta^{18}O$ values and fractionation in connection with refreezing of melt water. The preliminary annual balance values vary from ablation of more than 1.5 m of ice per year at an elevation of 200 m, to accumulation of about 0.3 m ice equivalent at an elevation of about 1300 m; balance occurs at around 700 m.

Ice velocity and deformation measurements

Ice flow velocities were measured by repeated relative GPS surveys at all stakes in the north-east glacier basin (Fig. 2). This data will serve as input for ice dynamic modelling. The stakes established and positioned in 1994 were re-positioned twice in 1995, in June and August. Strain rates were determined in three strain nets, one at the northern dome, one just below the equilibrium line at about 700 m a.s.l. and one at a location on the central part of the glacier tongue at an elevation of about 500 m a.s.l. All data have been processed to give preliminary summer, winter and annual values of vertical and horizontal velocities, as well as flow directions. The data show that horizontal surface ice velocities on the glacier tongue range from about 5 m/yr near the terminus to about 50 m/yr near the equilibrium line at about 750 m a.s.l. (Fig. 6) In the accumulation area, velocities are typically a few metres per year.

Stable isotope studies

In 1994 surface ice, snow and firn samples for $\delta^{18}O$ analysis were collected along the stakes in the glacier basin for comparison with the $\delta^{18}O$ record from the ice core at the southern dome. Preliminary analysis of the glacier basin samples showed unexpected large variations and trends (Fig. 6). In order to make a meaningful comparison of the $\delta^{18}O$ record from the surface of the ablation area with the deep drilling record, the surface $\delta^{18}O$ record needs to be corrected for variations in the $\delta^{18}O$ content of the ice in the accumulation area of the glacier basin. Samples from snow pits and SIPRE corings in the accumulation area of the glacier basin reveal a pronounced 'reverse' relationship of $\delta^{18}O$ with elevation; Fig. 6 illustrates a 4.5‰ increase of $\delta^{18}O$ in the accumulation area for a 550 m increase of elevation.

In order to shed light on the cause of these variations in $\delta^{18}O$ a more detailed sampling programme was carried out in August 1995; samples were taken at all stakes from stake 25 to 652, as well as at locations between the stakes. A total of 290 ice samples were taken from the glacier tongue area with 10 samples collected at each location; a further 60 samples of snow and firn were taken from the accumulation area during pit work and SIPRE coring.

The new repeated sampling confirmed the results from the 1994 sampling programme.

A similar 'reverse' $\delta^{18}O$ trend was found in the ice core

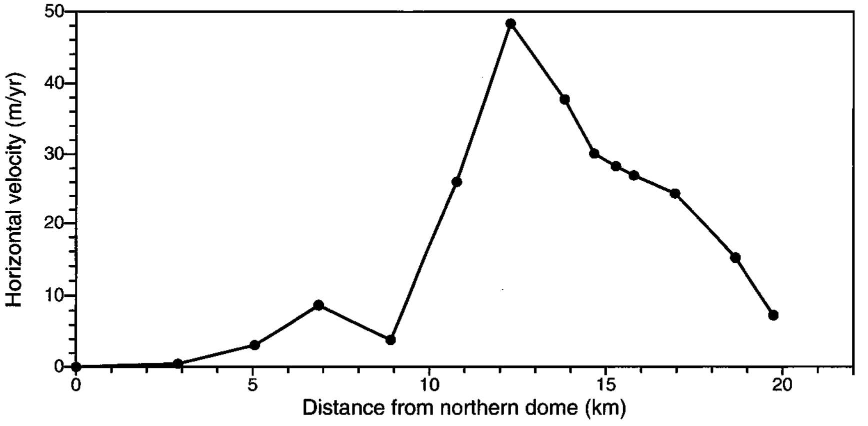

Fig. 5. Variation of horizontal ice surface velocity along the central ice flow line in the north-eastern glacier basin of Hans Tausen Iskappe. For location of central ice flow line see Fig. 2.

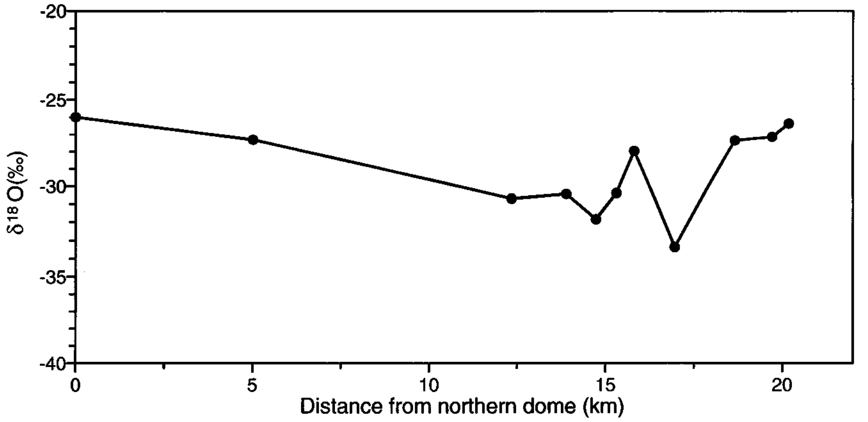

Fig. 6. $\delta^{18}O$ variation along the central ice flow line in the north-eastern glacier basin of Hans Tausen Iskappe based on sampling in 1994. For location of central ice flow line see Fig. 2. The equilibrium line is about 11 km from the northern dome. The 'reverse' $\delta^{18}O$ trend in the accumulation basin (0–11 km) is confirmed by additional samples collected in June 1995.

drilled at the southern dome (Hammer, 1995), which showed $\delta^{18}O$ values 1.5‰ lower in the bottom 100 m; such trends have no counterpart in other Arctic ice cap cores. Both reverse relationships might be due to heavy summer melting leading to the summer snow with high $\delta^{18}O$-values seeping away through the snow pack. This explanation is supported by the observation of extensive slush fields developed at elevations up to 1000 m in the accumulation area of the ice cap during July–August 1995.

Surface ice samples collected in 1994 near the terminus of the glacier tongue and on a glacier tongue south-east of the ice core drilling location on the southern dome (Fig. 1) indicated that ice from the last ice age was not present at the margin of Hans Tausen Iskappe. To confirm this observation 300 additional ice samples were collected in 1995 near the ice core drilling location along a two kilometre profile covering the outermost part of the ice tongue; the sampling interval was 5 m for the outermost kilometre, and 10 m for the remainder of the profile. This additional sampling confirmed the observation that ice from the last ice age is not present, suggesting that the ice cap may have melted away completely during the Holocene climatic optimum. The $\delta^{18}O$ record from the ice core drilled to bedrock at the southern dome of Hans Tausen Iskappe in spring 1995 supports this hypothesis; Holocene $\delta^{18}O$ values are present throughout (Hammer, 1995).

Discovery of biogenic material in the ice

During a foot traverse on August 19 a musk-ox carcass was found on the ice surface 500 m east of stake 400 on the glacier tongue (Fig. 2). Individual body parts were more or less intact, but distributed over a 10 m long stretch parallel with the direction of ice movement. Excavations in the ice upstream of the carcass revealed musk-ox meat and fur continuing down into the ice, indicating that the musk-ox had been transported within and melted out of the ice. Selected body parts were brought home for biological investigations and ^{14}C dating.

The discovery of the musk-ox may serve as an interesting natural tracer for dating the ice. However, this will depend on how the musk-ox was originally incorporated into the ice. Preliminary calculations of the age of the ice at the location of the discovery indicate an age of 500–1000 years.

Preliminary conclusions

The $\delta^{18}O$ surface ice sampling programme indicates that ice from the last ice age is not present at the margin of

Hans Tausen Iskappe, a conclusion supported by the ice core drilled at the southern dome (Hammer, 1995). The ice cap must thus have melted away completely during the Holocene climatic optimum. Glacial geological studies to the north of the ice cap carried out in 1994 (Landvik & Hansen, 1994), and earlier investigations south and west of the ice cap (A. Weidick, personal communication, 1995), show that areas adjacent to the present ice cap margin became ice-free after the last ice age about 6000–7000 years ago. It is thus likely, that any earlier ice cap became extinct some time after 6000 BP, and that the present Hans Tausen Iskappe started to build up in the mid-Holocene. By contrast, the Canadian Arctic ice caps at similar high northern latitudes can be shown to have survived the Holocene climatic optimum, which might indicate that eastern North Greenland is highly sensitive to climate change.

Results of the mass balance and englacial temperature studies, and studies of $\delta^{18}O$ variations, indicate the existence of an efficient warming mechanism probably due to development and refreezing of extensive slush fields. The heat produced may propagate to the bottom of the ice and raise the temperature of the basal layers with the effect of increasing ice flow velocities and enhancing the tendency for ice cap deterioration. Similar, but more pronounced, conditions are likely to have occurred during the Holocene climatic optimum leading to disintegration of the ice cap.

To quantify this conclusion in terms of modelling the varied processes involved, will require a major effort of data analysis, compilation and interpretation, as well as developing and running models for glacier mass balance and thermodynamics.

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The Danish Lithosphere Centre in 1995

Hans Christian Larsen
Director, Danish Lithosphere Centre

The Danish Lithosphere Centre (DLC) is funded by the Danish National Research Foundation and was established in 1994 (Larsen, 1995). In 1995 DLC undertook major field geological investigations in both West and East Greenland, and within the Ocean Drilling Program (ODP) drilling on the continental shelf offshore East Greenland. More than 50 national and international researchers were involved in DLC field geological programmes, and 25 researchers from ODP member countries took part in the offshore drilling operations. The general aims and scope of these activities as well as the continued development of the Centre are summarised below. Preliminary results of the 1995 work programmes are given by van Gool *et al.*, Larsen *et al.* and Brooks *et al.* (all this report).

The centre

The Danish Lithosphere Centre is established as an independent research unit hosted by the Geological Survey of Greenland (GGU) and the Geological Institute of the University of Copenhagen (GIKU). GGU was amalgamated with the Geological Survey of Denmark in 1995 to form the new Geological Survey of Denmark and Greenland (GEUS), and GEUS will thus replace GGU as one of the two host institutions. DLC will remain at its present premises at the Geological Institute.

In 1995 DLC expanded its staff with two guest researchers, two PhD students and a curator/geochemist. At present the centre employs 13 geologists and geophysicists, three PhD students and an administrative department leader. In addition to the DLC staff 12 Research Fellows from GIKU and GEUS are associated with the centre, and an additional 30 international partners from the USA, Canada, Australia, Norway, UK, Germany and The Netherlands are active in DLC work.

The additional funding in support of the centre's research plan obtained in 1994 (Larsen, 1995) has been further expanded in 1995 with support from the US National Science Foundation (NSF; two projects) and the Danish Natural Research Council (one post-doctorate scholarship).

The work of DLC in 1995 has been dominated by the planning and execution of the major data acquisition programmes. Preliminary results of the initial 1994 work have been presented at international meetings or submitted for publication.

Research plan and field operations in 1995

The DLC research plan builds on the application of multidisciplinary studies on selected geological problems of plate tectonic scale and significance. Two major topics have been selected for the first five years period: (A) Early Proterozoic amalgamation of Archaean continents into the North Atlantic craton as illustrated by the Nagssugtoqidian orogen in West Greenland; and (B) formation of the Tertiary volcanic rifted margin in East Greenland during the continental break-up of the northern North Atlantic (see also Larsen, 1995). Investigations in both of these study areas were initiated in 1994 (offshore investigations already in 1993; Larsen *et al.*, 1994, 1995 and Marker *et al.*, 1995) and these were continued in 1995 (Fig. 1). The first theme mainly involves geological studies, whereas the second theme is truly multidisciplinary involving marine geophysics, drilling (Ocean Drilling Program, ODP) and field geology.

Nagssugtoqidian orogen

Studies on the Nagssugtoqidian orogen in central West Greenland (Fig. 1) were carried out by a group of 20 geologists during July – August (van Gool *et al.*, this report).

The Nagssugtoqidian orogen in central West Greenland is part of a major trans-North Atlantic zone of Early Proterozoic (2500–1700 Ma) orogenesis by which older continental blocks were amalgamated into a large craton around 1900–1800 Ma ago (Bridgwater *et al.*, 1991). This presumably involved plate tectonic processes, i.e. ocean basin formation, build up of island arc complexes and closure of ocean basin, followed by continental collision and related mountain belt formation.

The Nagssugtoqidian orogen provides an excellently exposed deep crustal cross-section of the suture zone between suggested southern and northern Archaean continents. Investigations include the southern Nagssugtoqidian foreland, which in the Nuuk area further south contains some of the oldest known continental rocks (*c.* 3900 Ma;

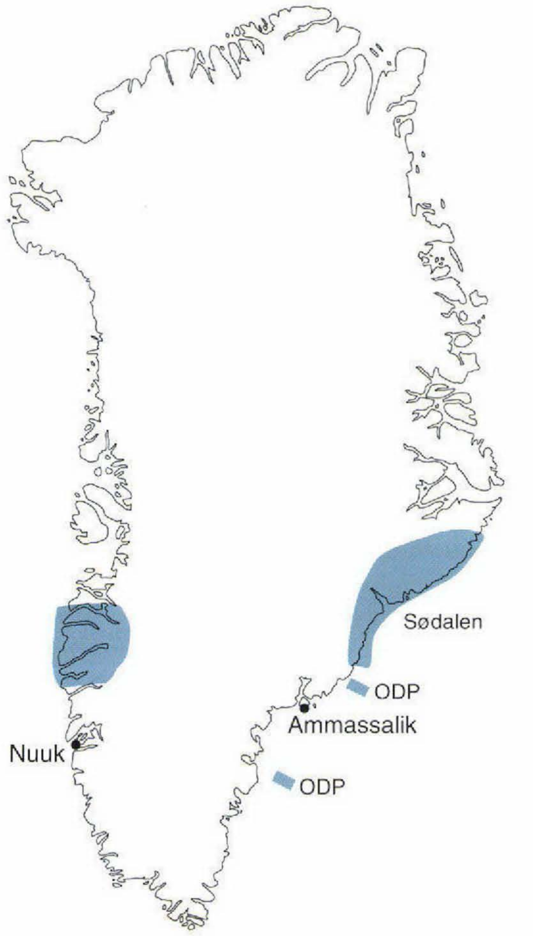

Fig. 1. Areas of DLC investigations in 1995.

e. g. Nutman *et al.*, 1993; Rosing *et al.*, 1996), and an area of *c.* 3500 Ma old gneisses identified close to the southern Nagssugtoqidian front (unpublished data, M. Rosing, 1996). A major, basaltic dyke swarm (Bridgwater *et al.*, 1995), possibly representing a rifting event, intruded the southern foreland at approximately 2050 Ma (A. P. Nutman, unpublished DLC data, 1994). Additional magmatism within the orogen is indicated by similar metasediment provenance (zircon) ages. The dyke swarm and the Archaean basement were subsequently involved in the Nagssugtoqidian deformation to the north of the foreland. The orogen comprises supracrustal sequences of Early Proterozoic age which may represent both continental margin and basin floor sediments (including possible basin floor igneous material). In addition, plutonic rocks representing juvenile island arc material (Kalsbeek *et al.*, 1987) and continental margin magmatism have been identified and dated to about 1930–1920 Ma (F. Kalsbeek and A. P. Nutman, unpublished data, 1996). During the Nagssugtoqidian deformation these key units were dismembered, stacked during thrust movement and interleaved with the Archaean gneisses. Late orogenic, in part strike-slip deformation partly transposed existing structures into steeply dipping to subvertical positions. The DLC investigations in 1995 addressed all these main elements of Nagssugtoqidian orogenesis (see van Gool *et al.*, this report).

East Greenland volcanic rifted margin

Studies on the early Tertiary continental break-up and associated magmatism in East Greenland were carried out by a group of 34 geologists and geophysicists from mid-July to early September (Brooks *et al.*, this report). This work was continuously supported by two helicopters in order to reach some of the most inaccessible areas in Greenland.

The voluminous plateau basalts of 55–60 Ma age along the East Greenland margin are the most extensive exposures of the massive volcanism related to the early Tertiary continental break-up and North Atlantic ocean basin formation. The products of this volcanic event, also manifested by offshore, seaward dipping reflector sequences (targeted in ODP Legs 152 and 163; Larsen *et al.*, 1994, this report), are estimated to have a total volume of several million cubic kilometres throughout the North Atlantic region (Eldholm & Grue, 1994) and to be related to the presence of unusually hot mantle below the region during break-up.

The thick basalt sequences represented onshore as well as offshore show chemical variations reflecting subtle chemical changes in the mantle source regions, which are thought to represent a mantle plume (Iceland mantle plume) ascending from great depths, perhaps from near the core–mantle boundary of the Earth (see White & McKenzie, 1995 for recent review). Intense dyke swarms in a coast-parallel belt record magmatism in a similar way to the basalts, and may preserve information on lava sequences which have since been lost by erosion. The dykes (and lavas, where preserved) also record the structural events associated with continental break-up. Finally, vertical movements of the Earth's crust (i.e. basin formation and uplift and erosion) are important, as they represent significant changes in the temperature and stress regime of the region. All these aspects (plateau lavas, dyke swarms and basin formation and uplift) have been at the forefront of DLC's work in East Greenland in 1995 (Brooks *et al.*, Larsen *et al.*, both this report).

ODP Leg 163 was planned to follow up on the successful Leg 152 to the South-East Greenland margin. The main objectives of these two legs were roughly similar to that of the onshore plateau basalt sampling programme (i.e. the volcanic development with time), but with the additional goals of examining in detail the continent–ocean transition, and to recover samples representing early pristine oceanic volcanism (Larsen *et al.*, this report). The cruise started

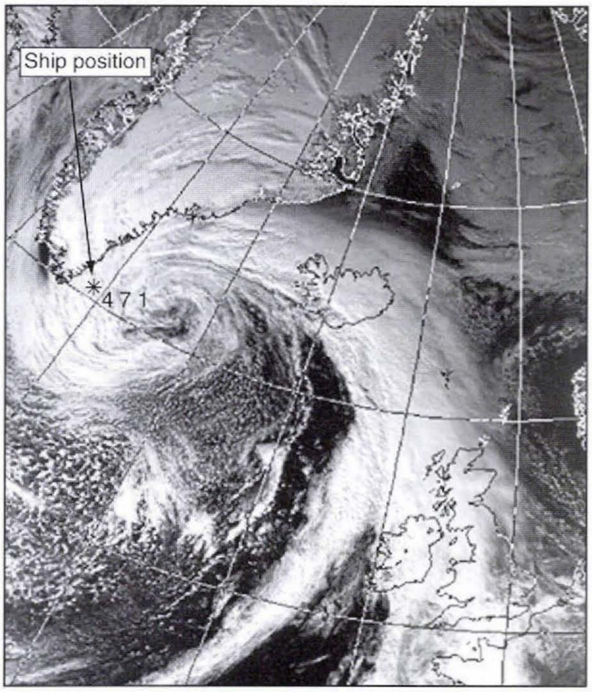

Fig. 2. Satellite image of the storm centre which developed over South-East Greenland 29 September. Wind forces of more than 100 knots (extra-tropical hurricane, force 2) and steep, frequent waves, exceeding 20 m in height were recorded on the ODP drill ship *JOIDES Resolution*, which was in a survival mode from the early morning of 30 September to about noon, 1 October.

from Reykjavik, Iceland on 7 September but soon after returned to Reykjavik for repairs following initial drilling problems and related damage to the equipment. Drilling was resumed on 16 September and continued until 29 September when a storm centre rising to strong hurricane disrupted activities (Fig. 2). During this fierce storm the ODP drilling ship *JOIDES Resolution* suffered severe damage, which excluded further drilling on Leg 163. Only three out of the six planned drill sites were drilled, and only one of these to the planned depth. This was an exceptional event never before experienced in 27 years of scientific ocean drilling.

Future work

Completion of the 1995 field programme in many ways secured the data background necessary to fulfil the research goals of the original DLC research plan for the period 1994–1998. However, within the present research plan and budget, one further major data acquisition programme is planned, a deep crustal seismic study (SIGMA; see also Larsen, 1995), which is scheduled for August – September 1996. SIGMA is a collaborative effort between DLC and Woods Hole Oceanographic Institution, USA. In addition, supplementary field geological work within the Nagssugtoqidian orogen may take place in 1997.

Clearly, the suspension of drilling on Leg 163 constitutes a significant deficiency in the total data set planned for the DLC rifted margin study. Thus, investigations of alternative (to ODP) drilling platforms capable of drilling to a few hundred metres depth on the East Greenland shelf have been initiated. It is hoped that most of the critical data gaps resulting from the early termination of Leg 163 can be filled through this type of supplementary drilling in 1997 or 1998. A preliminary proposal for drilling has been submitted to the Danish National Research Foundation.

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The Palaeoproterozoic Nagssugtoqidian orogen in West Greenland: current status of work by the Danish Lithosphere Centre

Jeroen van Gool, Mogens Marker, Flemming Mengel and field party

The Danish Lithosphere Centre (DLC) has now completed its second season of field work in the Nagssugtoqidian orogen of West Greenland. The work is aimed at studying the orogenic evolution of the Nagssugtoqidian orogen and comparisons with other Early Proterozoic orogens on the northern margin of the North Atlantic Archaean craton (see Larsen, this report). This paper presents the preliminary results from the field work and the current status of laboratory work related to this project.

In the period from 26 June to 25 August, 1995, field work was carried out in an area between latitudes 65°15′N (Maniitsoq) and 68°10′N (Ataneq and Arfersiorfik fjords) in West Greenland, covering a large portion of the Nagssugtoqidian orogen and part of its southern foreland (Fig. 1). Twenty scientists were involved in the field work, including nine from DLC, six external research partners and five M.Sc. students. In addition, seven other external partners are associated with the project through previous field work or ongoing laboratory studies (see Appendix).

The first field season in 1994 was aimed mainly at obtaining an overview of the different lithological and tectonic elements of the orogen, whereas the second summer was focused more on specific key areas and problems. Several of the sub-projects that were initiated in 1994 were continued. The main research themes of the 1995 field season were, from south to north:

- Configuration of the southern Archaean foreland.
- Structure, metamorphism and petrology of Kangâmiut dykes and their host rocks in the southern foreland and the orogenic margin.
- Structural and metamorphic development of the southern Nagssugtoqidian front.
- The structural development of the boundary zone between the southern and central segment of the Nagssugtoqidian orogen ('Ikertôq thrust zone').
- The Palaeoproterozoic Sisimiut charnockite complex, field relations, petrology and tectonic setting.
- Structure and lithology of the central segment of the orogen.
- The structure and metamorphism of the Nordre Strømfjord – Arfersiorfik flat belt and the nature of the boundary zone between the Archaean and the Palaeoproterozoic complexes.

Several laboratory studies associated with these field projects are currently being carried out on samples collected during the two field seasons. These include geochronology, geochemistry including isotope geochemistry, geothermobarometry and microstructural analyses.

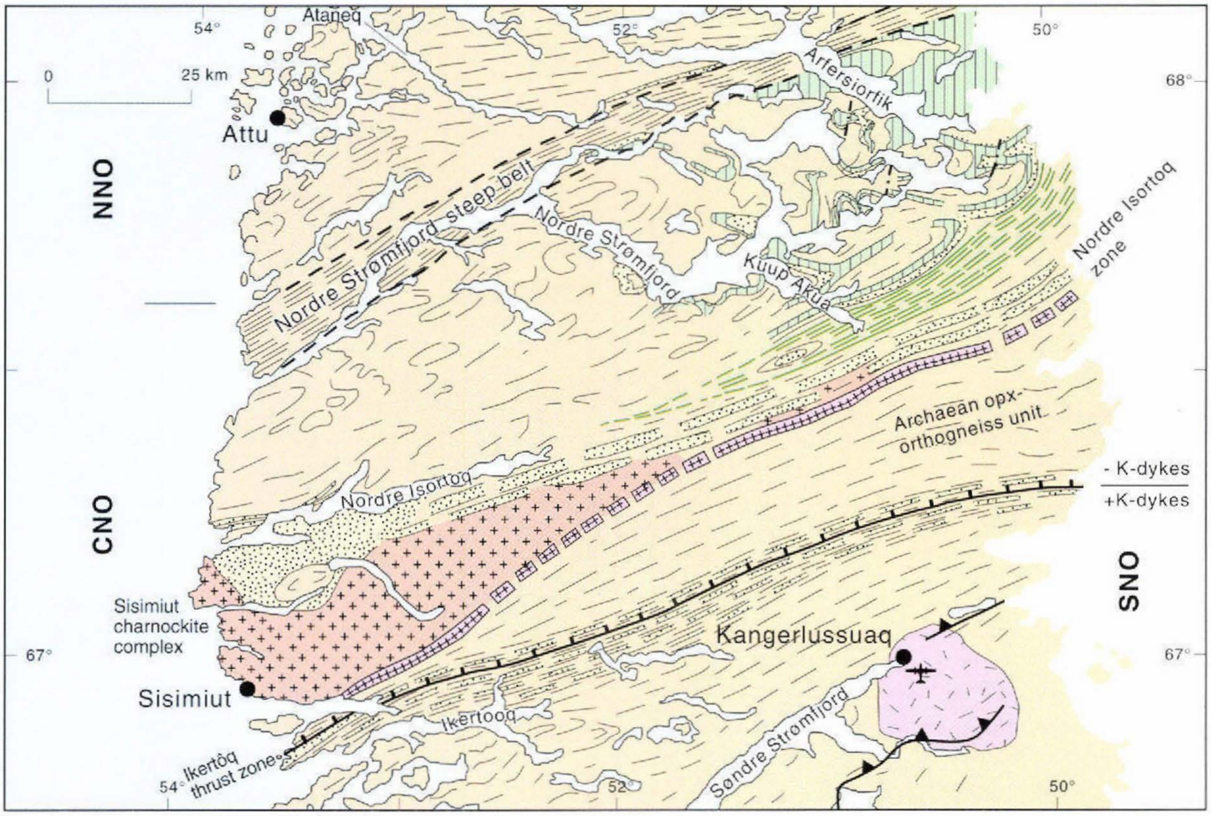
The Nagssugtoqidian orogen

The 1994 field season resulted in a new subdivision and a re-evaluation of structural elements in the orogen (Marker *et al.*, 1995). Field work was concentrated on outlining the main lithotectonic units and a supporting reconnaissance age dating programme was carried out (Kalsbeek & Nutman, in press).

Based on lithological, structural, metamorphic, geochronological, geochemical and geophysical features, the Nagssugtoqidian orogen of West Greenland can be subdivided into three ENE–WSW striking lithotectonic segments, which are bounded to the north and the south by Archaean blocks (Fig. 1).

The southern autochthonous foreland consists of a complex of Early to Late Archaean banded gneisses, granitoid intrusives and supracrustal rocks, all predominantly at granulite facies. These are intruded by the Kangâmiut dyke swarm of which one dyke has been dated at 2046 ±8 Ma (U-Pb zircon SHRIMP data, F. Kalsbeek, A. P. Nutman and D. Bridgwater, unpublished data, 1995). North of the southern Nagssugtoqidian front (Fig. 1; Escher *et al.*, 1975), these gneisses are variably reworked at amphibolite facies in the parautochthonous southern Nagssugtoqidian orogen.

The 'Ikertôq thrust zone' (Grocott, 1977; see Fig. 1) is a zone of increased strain which forms the boundary between the southern and central Nagssugtoqidian orogen. It is a significant lithotectonic break, since it marks the northern limit of the Kangâmiut dyke swarm and the southern limit of extensive Proterozoic intrusives. The central Nagssugtoqidian orogen can be subdivided into a southern 'steep belt' at granulite facies and a northern 'flat belt' at granulite facies in the west and amphibolite facies in the east. The metamorphism in this part of the orogen has been dated at *c.* 1850 Ma (Kalsbeek & Nutman, in press; J. Connelly, unpublished data, 1995) The transition from flat to steep belt broadly coincides with a zone of supracrustal rocks, which are most voluminous at Nordre



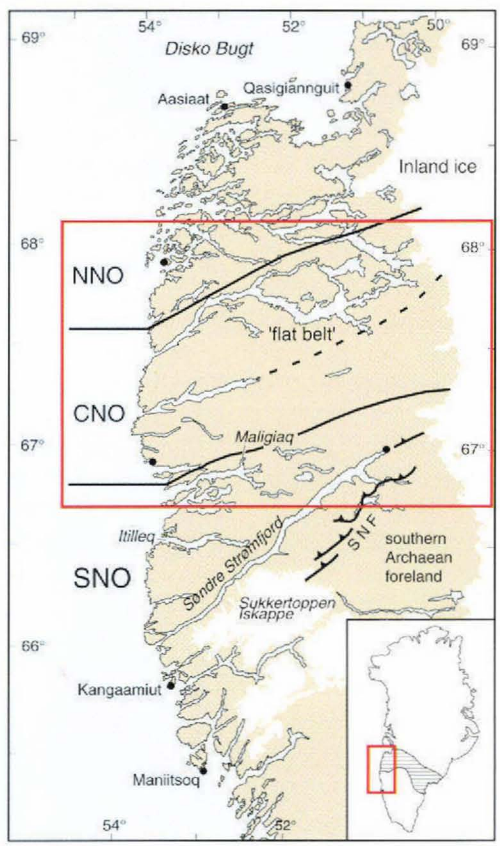


Fig. 1. Tectonic sketch map and location map of the Nagssugtoqidian orogen in West Greenland. SNO, CNO and NNO are the southern, central and northern segments of the orogen, respectively. SNF: southern Nagssugtoqidian front. +K-dykes/–K-dykes: Kângamiut dykes present/not present.

Fig. 2. Kangâmiut dykes in the central part of Søndre Strømfjord. The dykes are transposed to NNW-dipping orientations, but angular discordances and variations in thickness are preserved. Height of cliff c. 500 m.

Isortoq (Fig. 1). The south-western part of the central Nagssugtoqidian orogen is characterised by orthopyroxene-bearing gneisses of the Sisimiut charnockite complex, which have been dated at *c.* 1920 Ma (Kalsbeek & Nutman, in press). The south-eastern part contains gneisses of Archaean age which are similar in appearance to the Sisimiut charnockites. The flat belt in the north is characterised by Archaean basement orthogneisses, which are interleaved with a complex of Proterozoic rocks, including the Arfersiorfik quartz-diorite association (Kalsbeek *et al.*, 1987; Kalsbeek & Nutman, in press).

The transition from the central to the northern Nagssugtoqidian orogen has been tentatively placed at the Nordre Strømfjord steep belt (Marker *et al.*, 1995), but the nature and the position of the boundary is poorly constrained. The Nordre Strømfjord steep belt is a zone of localised deformation, which contains isolated strands of highly strained rocks (Hanmer *et al.*, submitted manuscript), but does not constitute a crustal scale shear zone as previously assumed (Bak *et al.*, 1975). The northern Nagssugtoqidian orogen is dominated by 2800 to 2700 Ma granitoid gneisses, with only few inclusions of presumed older rocks. They are variably deformed at amphibolite facies grade and contain metasedimentary layers which are folded on a kilometre scale. The ages of deformation and metamorphism are poorly constrained and hence the northern limit of Nagssugtoqidian tectonism is presently not known.

New results

During the 1995 field season the emphasis was on a number of specific projects, which were carried out by members of the field party in different combinations. The main effort was in the southern and central segment of the Nagssugtoqidian orogen and its southern foreland. Preliminary results are summarised below from south to north.

Southern Archaean foreland

The Archaean foreland east of Sukkertoppen Iskappe consists of an Early Archaean (pre-3500 Ma, M. Rosing & A. P. Nutman, unpublished data, 1995) gneiss complex which is juxtaposed against Late Archaean gneisses (*c.* 2700 Ma) along prominent lineaments. The timing and nature of movement along these lineaments is uncertain. A suite of metamorphosed mafic dykes, which are tentatively correlated with the Kangâmiut dyke swarm, cuts the Early Archaean complex, but has not been recognised in the younger gneiss complex. These observations suggest that the two Archaean complexes were juxtaposed subsequent to the intrusion of the dykes. This would require significant Palaeoproterozoic tectonic activity in the southern foreland to the Nagssugtoqidian orogen.

Kangâmiut dykes

The emplacement of the Kangâmiut dyke swarm at *c.* 2000 Ma, just before the main pulse of Palaeoproterozoic orogenesis, makes it a prime target for studies of Nagssugtoqidian deformation and metamorphism. The dykes were studied and sampled in a section along the coast from Maniitsoq in the southern foreland, to Itilleq fjord within the southern Nagssugtoqidian orogen, for structural, metamorphic, igneous, geochemical and geochronological purposes.

Between Maniitsoq and the mouth of Søndre Strømfjord, far south of the Nagssugtoqidian front, the Kangâmiut dyke swarm is variably affected by deformation and metamorphism. Isolated, wide dykes show foliated centres with metamorphic mineral assemblages (garnet-hornblende-plagioclase), while dyke margins and thinner dykes generally show well-preserved igneous textures and minerals. Dykes are broadly NNE–SSW trending and any observed deformation has a component of sinistral shear. Closer to the orogen, within tens of kilometres of the southern front, dyke margins are deformed and metamorphic replacement of igneous minerals occurs throughout the dykes. Within the southern Nagssugtoqidian orogen, the dykes are variably boudinaged, foliated and transposed to gently NW-dipping orientations, parallel with the Palaeoproterozoic gneissic fabric (Fig. 2).

Observations both within and outside the southern segment of the orogen, indicate that several generations of Proterozoic dykes are present. Although the majority of the dykes appear to be broadly contemporaneous, a small number of dykes truncate earlier dykes and structures. This may indicate late- to post-Nagssugtoqidian emplacement, or that many of the supposed Nagssugtoqidian structures are in fact pre-Nagssugtoqidian.

The southern Nagssugtoqidian front

The inland portion of the southern Nagssugtoqidian front is a sharp boundary separating rocks with penetrative, overall NW-dipping fabrics within the orogen, formed by transposition of older structures at amphibolite facies conditions, from rocks to the south which preserve older gneissosity and Archaean granulite facies metamorphism. In the case of Late Archaean granites which are cut by the front, e.g. in the Søndre Strømfjord Airport/Kangerlussuaq region, the front marks the southern limit of a penetrative fabric. The boundary of the Nagssugtoqidian orogen is best displayed by the state of deformation of the Kangâmiut dykes, as described above (Fig. 2). The front is defined by a left-stepping array of discontinuous, narrow, high-strain zones that show minor oblique-sinistral thrust displacement. The fact that lithologies can be traced across the front indicates that displacement on this structure is limited.

In the coastal region, the Nagssugtoqidian front is a diffuse rather than a sharp boundary, indicated by the progressive reorientation of older structures. The 'Itivdleq shear zone', which was previously assumed to represent the western continuation of the Nagssugtoqidian front, is a steep belt, containing an array of isolated, sinistral high-strain zones, which re-utilise pre-existing Archaean shear zones.

The boundary between the southern and central Nagssugtoqidian orogen

This boundary is characterised by a steeply dipping straight belt with increased strain compared to the remainder of the southern segment of the orogen. It was introduced by Grocott (1977) as the 'Ikertôq thrust zone' which accommodated major thrust displacement. Panels of Proterozoic supracrustal rocks (Kalsbeek & Nutman, in press; D. Scott and D. Bridgwater, unpublished data, 1995) are interleaved with Archaean gneisses (Fig. 3). Detailed mapping indicated that this interleaving is a result of combined thrust stacking and large-scale isoclinal folding. Gneissic banding and sedimentary layering are locally truncated by thrust-like structures and presumed thrust-related folds were observed. The thrust surfaces are not characterised by higher strain, which may suggest that thrusting originated at shallow crustal levels by brittle mechanisms and proceeded while the thrust stack was being buried. During subsequent ductile deformation folds were tightened and re-oriented and thrusts as well as existing foliations were transposed into a steeper orientation.

The metamorphic transition from amphibolite to granulite facies, immediately south of the boundary between the southern and central segment of the orogen, lies within this fold-and-thrust belt, but there are no obvious indications that the location of the boundary is a result of the thrusting (cf. Grocott, 1979). The nature of the boundary with the Sisimiut charnockite complex to the north is enigmatic. Intrusive sheets of the charnockite complex locally appear to truncate imbricated gneisses and supracrustal rocks, which places an important constraint on the timing of sedimentation and thrusting in this area.

Central Nagssugtoqidian orogen

Sisimiut charnockite complex

Orthopyroxene-bearing gneisses in the Sisimiut area belong to the Sisimiut charnockite complex in the southwestern part of the central Nagssugtoqidian orogen (Fig. 1) and have been dated at *c.* 1920 Ma (Kalsbeek & Nutman, in press). Extensive partial melting of the country rocks, both metapelites and Archaean gneisses, and preliminary geochemical and isotopic data indicate that this is an inhomogeneous intrusive body which has been variably contaminated by its host rocks and is therefore likely to have been emplaced by intrusive, rather than structural mechanisms. Orthopyroxene is interpreted as a primary phase, thus making the intrusive body a charnockite *s.s.* This Palaeoproterozoic charnockite complex is very similar in age and compositional characteristics to charnockite suites in other North Atlantic Palaeoproterozoic provinces (e.g. Campbell *et al.*, 1995) and thus establishes a firm link between the Nagssugtoqidian orogen and other Palaeoproterozoic belts around the North Atlantic.

The boundaries of the Sisimiut charnockite complex are difficult to constrain, since most of the host rocks are ortho-

Fig. 3. Panel of Proterozoic supracrustal rocks (buff colour) within Archaean gneisses of the 'Ikertôq thrust zone', Maligiaq. The gneisses are intruded by Kangâmiut dykes. Height of cliff *c.* 300 m.

pyroxene-bearing gneisses with similar field-appearances, but which yield Archaean ages. To the north the charnockite complex was intruded into a voluminous package of supracrustal rocks, resulting in a diffuse northern boundary. Results of the reconnaissance age dating programme carried out early in 1995 (Kalsbeek & Nutman, in press) indicated that the charnockites of Proterozoic age are restricted mainly to the western part of the southern Nagssugtoqidian orogen, but thin strands continue far to the east (Fig. 1). Anomalously high Ba concentrations in stream sediment samples (Steenfelt, 1993) from the south-western part of the central Nagssugtoqidian orogen appear to coincide with known occurrences of the Sisimiut charnockite complex and may aid in defining the regional extent of the body. This will be tested by analyses of samples collected in 1995 from the presumed eastern boundary zone of the charnockite complex.

Nordre Isortoq zone

Substantial amounts of mainly psammitic and pelitic metasediments occur around Nordre Isortoq (Fig. 1). These form a wedge between the 'flat belt' to the north and the Sisimiut charnockite complex to the south and thus outline the Nordre Isortoq zone, which is characterised by pronounced partial melting of the metasediments. The zone narrows to the east, but can be traced as an up to 4 km wide belt all the way to the Inland Ice.

A several kilometre wide tract of syn-kinematic granites, which have been dated at *c.* 1835 Ma (two samples, U-Pb on zircon by SHRIMP, Kalsbeek & Nutman, in press), transect the southern part of the central Nagssugtoqidian orogen (Fig. 1). In the west the granites are found south of known occurrences of the *c.* 1920 Ma old Sisimiut charnockite complex, while the eastern occurrences are slightly south of the supracrustal rocks of the Nordre Isortoq zone (Fig. 1).

Zircons from samples of the metasediments in the Nordre Isortoq zone are of Archaean age (Kalsbeek & Nutman, in press). It is currently assumed that the sediments were derived from an Archaean continent and deposited on a continental margin. These sediments contrast strongly in provenance, volume, setting and composition from those of the northern part of the central Nagssugtoqidian orogen, which predominantly contain Palaeoproterozoic zircons and are interpreted as deposited in an island arc environment.

Fig. 4. Rock face at Kuup Akua exposing the contact between pale Archaean tonalitic gneisses underneath dark dioritic gneisses and supracrustal rocks of Proterozoic age. Thin slices of marble and calc-silicates occur at the contact and within the Archaean gneisses. Height of section *c.* 350 m high.

Eastern Nordre Strømfjord region

The 'flat belt' at the eastern end of Nordre Strømfjord has a lower metamorphic grade and is less intensely deformed than the remainder of the central segment of the orogen, and structures related to the early stages of Nagssugtoqidian orogeny are better preserved. Previous field observations, combined with results from the reconnaissance dating programme, suggested the presence of a thrust system which emplaced Proterozoic quartz-diorites on top of Archaean tonalitic gneisses often separated by supracrustal rocks (Fig. 4; Kalsbeek & Nutman, in press). The area was revisited to test this hypothesis by geometric and structural analysis of the Archaean and Proterozoic rocks, and to collect samples for further geochemical, geochronological and metamorphic studies.

The field work showed that Archaean gneisses are interleaved with a complex of Proterozoic intrusive and supracrustal rocks, including marble, pelite, semi-pelite and volcaniclastic rocks, as well as ultramafic (peridotitic) rocks. Contacts between the Archaean and Proterozoic units are often highly strained, suggesting that they were juxtaposed by thrusting, but large scale isoclinal recumbent folds were also found suggesting that fold nappes may exist. The Archaean gneisses did not form a stable basement upon which the Proterozoic gneisses were emplaced, but were intimately involved in the thrusting event. Kinematic indicators suggest predominantly top-to-the-east transport, but it is not certain whether this kinematic framework is related to the emplacement of the thrust sheets or represents a later event. The rocks in the northern part of the central Nagssugtoqidian orogen were folded into complex dome-and-basin interference patterns, while the enveloping surfaces of the thrust sheets remained sub-horizontal.

Supporting projects

All field projects in the Nagssugtoqidian orogen are supported by laboratory work, including geochemical, geochronological, metamorphic and microstructural studies. A few of the laboratory studies are of a regional reconnaissance nature, but most highlight detailed aspects of the geology of the orogen. Some of the more specific projects include:

- Timing of igneous, metamorphic and structural events as well as provenance studies of metasediments. This is carried out by U-Pb dating (SHRIMP, TIMS and Laser Ablation Microprobe ICP-MS) of zircon, sphene, rutile and monazite, and by Ar–Ar dating of hornblende.
- Metamorphic studies, aimed at the reconstruction of P–T paths for different tectonic elements in the orogen, and correlation of these with structural observations and radiometric age determinations.
- Geochemical and isotope studies aimed at determining the sources, emplacement processes and tectonic settings of Proterozoic intrusive rock suites in the orogen.
- Microstructural analyses of samples from key tectonic zones in the orogen in order to determine strain paths, deformation mechanisms and kinematics of selected rocks and to constrain the relative timing of deformation with respect to metamorphism.

Conclusions

Through a multidisciplinary approach, the two field seasons and the associated laboratory work have led to a much better understanding of the tectonic evolution of the Nagssugtoqidian orogen. Several elements typical of modern collisional orogens have been recognised in the Nagssugtoqidian orogen, including syn-orogenic sedimentary sequences, island arc intrusives and supracrustal rocks, peridotitic ultramafic rocks, imbricate thrust stacks, high grade metamorphism as a result of crustal thickening and large Proterozoic intrusive bodies. Speculations as to the collisional nature of the orogen (e.g. Bridgwater *et al.*, 1973), can now be more firmly postulated. The observations all support the interpretation that the Nagssugtoqidian orogen displays a deep crustal section through the locus of collision of two Archaean crustal blocks during the Palaeoproterozoic.

Further field work is planned for the 1997 season, when work will focus on the central and northern segments of the orogen. Particular targets include the Nordre Isortoq suite of metasediments and their relationships to the Sisimiut charnockitic complex in the south and the gneisses to the north. The transition from the central to the northern segment of the orogen across the Nordre Strømfjord steep belt will be further investigated. In addition, future research projects are expected to emerge as field data are compiled and interpreted and as results of ongoing laboratory work become available.

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Geochronological analyses by SHRIMP were funded by DLC, with additional support from the Geological Survey of Denmark and Greenland (GEUS), the Danish Research Councils (grant to D. Bridgwater) and the Schuurman funds (grant to F. Kalsbeek). David Scott provided LAM ICP-MS analyses of selected metasediment samples.

Appendix:
The 1995 field party in the Nagssugtoqidian orogen:
G. Manatschal, M. Marker, F. Mengel and J. van Gool (DLC), D. Bridgwater, B. Hageskov and M. Rosing (University of Copenhagen and DLC), L. Løfqvist, H. E. Olsen, D. Ulfbeck and L. Wichmann (University of Copenhagen), F. Kalsbeek and A. Steenfelt (GEUS and DLC), P. S. Jensen (University of Aarhus, Denmark), B. den Brok and C. Passchier (Johannes Gutenberg University, Mainz, Germany), L. Campbell (University of Colorado, Boulder, USA), J. Connelly (University of Texas, Austin, USA), K. Mayborn (University of California, Davis, USA) and B. Willigers (Vrije Universiteit Amsterdam, The Netherlands).
External research partners: A. Cadman (Leicester University, UK), S. Hanmer and D. Scott (Geological Survey of Canada, Ottawa, Canada), L. Kriegsman (University of New South Wales, Sydney, Australia), G. Nichols (Maquarie University, New South Wales, Australia), A. P. Nutman (Australian National University, Canberra, Australia) and M. Whitehouse (University of Oxford, UK).

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The East Greenland volcanic rifted margin – onshore DLC fieldwork

C. Kent Brooks and field parties

In accordance with the main objectives of the Danish Lithosphere Centre (DLC) research plan (Larsen, this report), the main onshore field work in East Greenland in 1995 had the following aims: (1) to collect from the entire exposed sequence of lavas in the Blosseville Kyst region and connect up existing work in the Scoresby Sund region with that around Kangerlussuaq; (2) to make comprehensive collections from the dyke swarms, establish their temporal relationships and to describe the structures associated with them; (3) to collect material for fission track dating from as extensive an area as possible, with the aim of documenting the timing and magnitude of uplift before, during and subsequent to the volcanic episode. In addition, a number of other tasks were carried out taking advantage of the logistic apparatus already established. In particular, a Geological Survey of Denmark and Greenland (GEUS) project, supported by DLC and Danish Oil and Gas Production A/S (DOPAS), was carried out in the Kangerlussuaq sedimentary basin and is expected to produce results of major interest to DLC (see M. Larsen *et al.*, this report).

In summary, the main objectives of this research are to document the chemical changes of the volcanic parents (magmas), to determine both the absolute and relative timing of the different magma types, and to correlate these events with both stretching and vertical movements within the Earth's crust. This ambitious programme will take some years of laboratory studies to realise and includes comprehensive major element, trace element and isotopic studies. A comprehensive radiometric dating programme is being carried out in collaboration with R. A. Duncan, Oregon State University.

Field work in 1995 was carried out from a base at the airstrip at Sødalen at the head of Miki Fjord (Fig. 1) and covered an area of approximately 50 000 km^2. It involved 34 scientists (see Appendix) and two helicopters for the period 13 July until 15 September. All the main objectives of the expedition were achieved, including visits to areas hitherto regarded as inaccessible.

The basalts of the Blosseville Kyst region form a mountainous area, which includes the highest mountains within the Arctic Circle. During field work in 1995, a region of about 30 000 km^2 between Miki Fjord and Sortebræ (Fig. 1) was investigated in a number of large composite sections, designed to cover the entire lava stratigraphy in both coastal and inland areas, and also to cover possible north–south variations. The sections were based on information obtained by the aerial photography acquired in 1994 (H. C. Larsen *et al.*, 1995), where colour stereo images were obtained covering approximately 1600 line-kilometres of valley and fjord walls. From this it was determined that the succession reaches a total thickness of at least 6 km, probably closer to 7 km, in the Sortebræ area (Fig. 1). A number of sampling profile sites were identified spanning the whole lava succession and ensuring completeness of the sample coverage. During the summer of 1995 a further 650 line-kilometres of airborne stereo photographs were acquired, largely in the plateau basalts but also covering other aspects of DLC's work in the area.

Prior to the 1995 field season it was known that the onshore lavas between latitudes 68° and 70°N can be divided into three groups (Wager, 1947; Brooks *et al.*, 1976; Brooks & Nielsen, 1982), which are distinct both in the field and petrologically. We have used this conventional grouping pending their formal redescription: the lower basalts, the plateau basalts and youngest Prinsen af Wales Bjerge basalts.

The lower basalts

Previous studies (Brooks *et al.*, 1976; Nielsen *et al.*, 1981) have shown that the lithology of the lower basalts succession, which outcrops in the area between Kangerlussuaq and Nansen Fjord, is very different from the plateau basalt succession to the north, as it predominantly consists of compound flows with numerous clastic horizons. Most notable is the occurrence of highly magnesian lavas (picrites) which have an enriched geochemical signature.

The lower basalts succession was studied and sampled by a group of four scientists from field camps using helicopter support. In addition to extreme topography, the region presents numerous problems due to the pervasive alteration in this deep level of the lava pile, the restricted continuity along strike of many of the units and the presence of numerous sills which completely obscure the stratigraphy in some areas. Fourteen profiles, covering *c.* 5000 m of

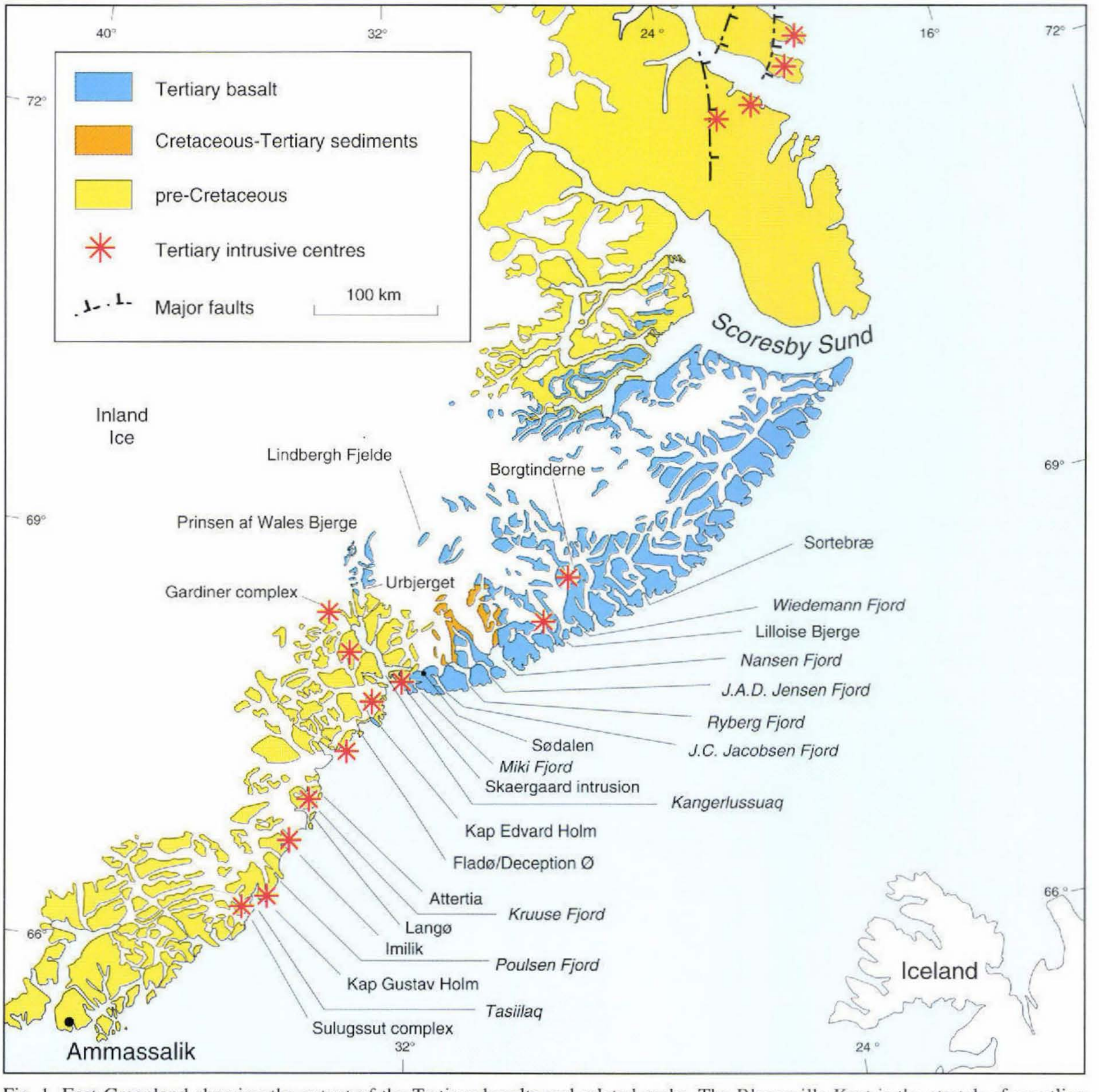

Fig. 1. East Greenland showing the extent of the Tertiary basalts and related rocks. The Blosseville Kyst is the stretch of coastline between Kangerlussuaq and south of Scoresby Sund.

stratigraphy, in Miki Fjord, J. C. Jacobsen Fjord, Ryberg Fjord, J. A. D. Jensen Fjord and Nansen Fjord (Fig. 1) were studied in detail and the entire succession was sampled.

The lower basalts are traditionally regarded as comprising the Vandfaldsdalen and Miki Formations (Soper *et al.*, 1976) with the transition to the overlying plateau basalts marked by a prominent tuff sequence, known as the 'Main Tuffs' (Wager, 1947) or Hængefjeldet Formation (Soper *et al.*, 1976; Nielsen *et al.*, 1981). This division was established in the western part of the area (i.e. in Miki Fjord and J. C. Jacobsen Fjord), the eastern part being relatively unknown. It was possible to follow the stratigraphy as far as Ryberg Fjord, although the thickness of the Miki Formation appears to thin considerably east of J. C. Jacobsen Fjord. At the same time, the Vandfaldsdalen Formation, which overwhelmingly consists of lava flows in the west, with subordinate volcanogenic sediments, pillow breccias (Fig. 2) and quartzitic sandstones, becomes almost exclusively hyaloclastite breccias in the east. This facies change indicates that during volcanism the depositional basin deepened towards the east.

It proved difficult to correlate eastwards of Ryberg Fjord.

Fig. 2. Pillow breccias in the lower basalts of Sødalen. Well-formed pillows and pillow fragments with glassy (now altered) margins are enclosed in altered hyaloclastite lapilli tuff. While some of the lower basalts are subaqueous, the bulk are subaerial.

There are many sills and the succession in J. A. D. Jensen Fjord is dramatically different from the portion of the succession to the west. Lowermost in the sequence at this locality are thick flows, 10–15 m thick, interbedded with reddened and locally scoriaceous deposits. This sequence is overlain by 4–15 m thick olivine-pyroxene-phyric flows. Plagioclase-olivine glomerophyric flows dominate the upper portions of the J. A. D. Jensen Fjord section. These latter units may be part of the plateau basalts, although a specific correlation cannot be made at this time.

The plateau basalts

Throughout the field season 2–4 field teams worked in the plateau basalts. Nearly 30 km of continuous profile was sampled, amounting to about 2200 samples. Special studies of the zeolite zonation and of laterite horizons were also carried out, the latter with a view to reconstruction of palaeo-climates.

The base of the succession is exposed in the southern part of the region, where volcanogenic sediments, interpreted as lahars, are present over large areas and overlie basement gneisses (which have a very irregular topography) or Cretaceous–Paleogene sediments of the Kangerdlugssuaq Group (Nielsen *et al.*, 1981). The correlation with the lavas and volcanoclastic rocks south of Nansen Fjord (lower basalts, Nielsen *et al.*, 1981) is not evident and awaits further photogrammetric studies. However, field observations using distinctive lithologies, such as phenocryst content and size, have allowed a tentative correlation to the north with the earlier established formations in the Scoresby Sund region (L. M. Larsen *et al.*, 1989). Lavas lithologically similar to those of the Milne Land, Geikie Plateau, Rømer Fjord and Skrænterne Formations are present in large parts of the investigated region. The Geikie Plateau and Rømer Fjord Formations are thickest in the coastal areas, and the Rømer Fjord Formation appears to wedge out completely in some inland areas. Several horizons of olivine-phyric magnesian lavas (Fig. 3) were found, especially in the lower part of the succession. The uppermost formation, the Skrænterne Formation, is mostly above exposure level in the south-eastern half of the region.

The Skrænterne Formation, previously thougt to be the uppermost unit within the plateau basalts, was locally found to be overlain, without any apparent unconformity, by a few, very fresh lavas of an alkaline nature. At present it is not known whether there is any correlation of these flows to the alkaline lavas within the Prinsen af Wales Bjerge (see below).

Eruption sites were found at several localities in both coastal and inland areas, and in both low and high parts of the succession.

Regional studies of the zeolites suggest that a well developed pattern of zeolite zones exists. The zones dip with the basalt stratigraphy, indicating that low-grade metamorphism pre-dated tectonism in the lava pile.

A number of tilted fault blocks were identified in a broad zone along the coast extending from 30 km to more than 100 km inland. Along the coast the lavas dip seaward at up to 12°.

The Prinsen af Wales Bjerge basalts

These lavas overly the plateau basalts in a series of nunataks, known as the Prinsen af Wales Bjerge, north of the head of Kangerlussuaq (Figs 1 & 4). They are reported to show irregular dips, in contrast to the plateau basalts, and to consist of alkaline types, in contrast to the uniformly tholeiitic character of the preceding volcanism (Wager, 1947; Anwar, 1955).

In 1995 a 2-man team collected detailed profiles in the nunataks north of inner Kangerlussuaq. Additional sites were visited by helicopter.

Wager (1947) believed the irregular dips of these lavas to represent near-vent facies. However, work in 1995 suggested that in some cases they are caused by draping of palaeo-river valleys cut into the top of the plateau basalts, although no unequivocal example of this interpretation could be found. The nunataks have an unusual rounded topography, which may reflect a pre-Pleistocene land-form. Glaciers draining the Inland Ice have sliced into this earlier configuration and have steep-sided margins. Exposures are poor above the present major glaciers.

At least in some cases, variable dips do represent the flanks of crater areas as suggested by Wager (1947). One of these structures was visited and found to contain a coarse-grained plutonic rock filling the central vent.

Anwar (1955) reported that the Prinsen af Wales lavas

Fig. 3. Part of the plateau basalt succession from the Geikie Plateau Formation in the nunatak zone of Lindbergh Fjelde more than 100 km inland from the coast. The light grey series are picrites. The discovery of widespread high magnesian lavas will simplify the study of mantle melting processes during the evolution of the volcanic rifted margin. Photo: A. K. Pedersen.

are weakly alkaline and contrast compositionally with the underlying tholeiitic 'Plateau Basalts'. Pyroxene-phyric lavas are common and picritic and glassy types were observed. These lithologies are rare to absent in the plateau basalts, where plagioclase is the most common phenocryst phase.

The most westerly nunatak (Lindsay Nunatak in Fig. 4) was found to have picritic lavas at the top, underlain by fluvial sediments containing a coarse-grained conglomerate. Blocks from this conglomerate contain a wide variety of alkaline rocks, including some with eudialyte, a mineral known only from the Gardiner complex, although this is not thought likely to be the source. It is suggested that the conglomerate was deposited by westwards-flowing rivers, following the geomorphological reconstruction of Brooks (1979). These rivers may be those which carved the palaeovalleys in the Prinsen af Wales nunataks.

Dyke swarms

The East Greenland coast is famous for its impressive dyke swarm originally reported by Wager & Deer (1938), which has been re-interpreted by Nielsen (1975), Nielsen & Brooks (1981) and Myers (1980). The dyke swarm is intimately associated with a major coastal flexure and is an important part of the history of break-up of this part of the North Atlantic (e.g. Larsen, 1978).

DLC studies on the dyke swarm in 1995 were focused in particular on: (1) establishment of the time relationships between different generations of the dyke swarm; (2) establishment of any differences along the dyke swarm with relation to the assumed centre of a proto-Icelandic plume; (3) whether the segmentation described by Myers (1980) can be confirmed; (4) whether the chemical types already established in the Kangerlussuaq area (Nielsen, 1978; Gill *et al.*, 1988) can be recognised in distal regions; and (5) the mechanism of flexuring.

An important question to answer is whether the North Atlantic opened by rift propagation from south to north (e.g. Larsen, 1988) or has opened from the hot-spot centre due to stresses caused by the mantle plume (e.g. Brooks, 1973).

With these aims in mind detailed profiles across the dyke swarm were made at six selected localities: J. C. Jacobsen

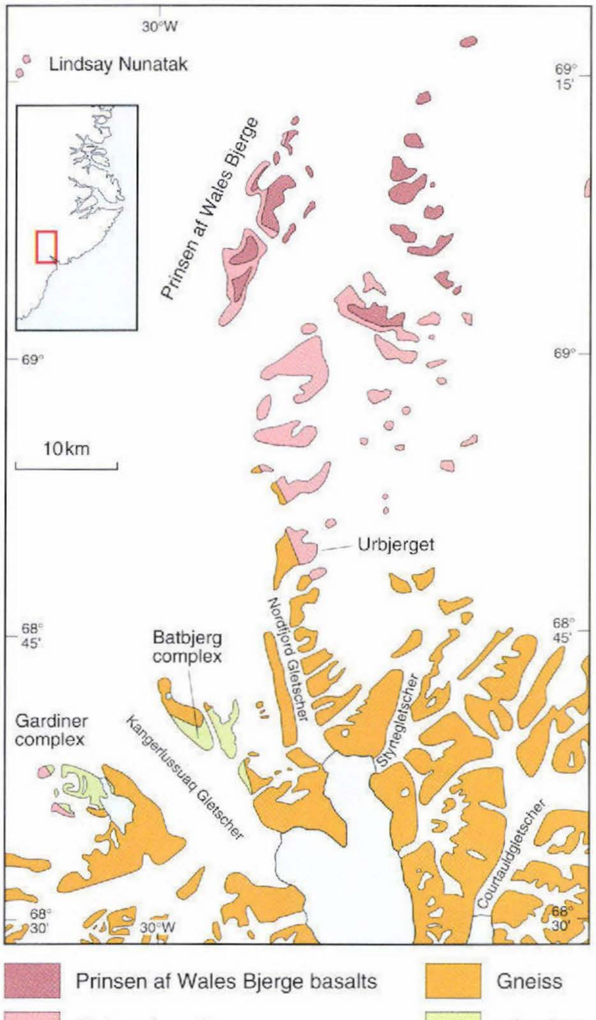

Fig. 4. Sketch of the area of the Prinsen af Wales Bjerge (after Wager, 1947). Note that the Batbjerg Complex is of Caledonian age.

Fjord, Kap Edvard Holm, Fladø, Deception Ø, Attertia and Langø to the south along the coast (Fig. 1). In addition, shorter excursions were made to outlying areas. Each transect was 10 to 20 km in length. J. C. Jacobsen Fjord lies in the east–west section of the coast to the east of Kangerlussuaq, the sector where some of the earlier studies were carried out (Nielsen, 1978). The other localities lie to the south, where the coastline is more north–south trending and the only previous work is the geochemical study of Gill *et al.* (1988) from Fladø. Kangerlussuaq is thought to form a triple junction, with the fjord forming the third arm or 'failed arm' (Brooks, 1973). Sampling was carried out in the interior of Kangerlussuaq and in the area of sediments to the north of Ryberg Fjord and J. A. D. Jensen Fjord.

Work ranged from broad regional studies to very detailed investigations. Detailed measurements of thicknesses and attitudes of the dykes over long profiles, perpendicular to the general trend of the outer coast, were carried out with the aim of quantifying the degree of magmatic extension. Data were collected in the six transects measuring 1700 dykes altogether. One profile alone (that on Langø) contains over 500 dykes (Fig. 5). In the course of this work, 208 rock samples were taken for chemical analysis (see below). It is clear that certain systematic changes are found along the coast. South of Kangerlussuaq there is a gradual clockwise rotation of the average strike from south to north and there appear to be at least three distinct sections, although it is not clear whether these correspond to the segments described by Myers (1980). In the area of Attertia, Myers' dyke clusters could not be identified.

The geochemically orientated studies used detailed mapping of reference areas of limited extent within each segment of the swarm, supplemented by reconnaissance work over larger areas. In the reference areas, all dyke relationships were recorded and complete sampling was carried out in order to establish the chronological sequence of geochemical types. Ultimately it should be possible, using chemical fingerprinting, to correlate these dykes with known lava types. A collection of samples was made of material thought to be suitable for the extraction of zircon or baddeleyite for radiometric dating of the dyke swarm.

Structural work, to determine the deformation style of the East Greenland margin during extension, was carried out as an integral part of the above mentioned projects. Drilling of selected dykes as well as gabbro bodies was carried out to obtain samples for palaeomagnetic studies to determine the degree of rotation of the dykes.

Observations made in areas of basement gneisses, sediments and basalts, and at seaward, middle and inner parts of the transects will give information on the modes of strain accommodation at various levels and locations within the margin. Most of the transects are located in areas of moderate rotation, but highly rotated areas are exposed at Nuuttuaq in Poulsen Fjord (just south of Imilik in Fig. 1) and Deception Ø. One of the major discoveries of the season was the discovery of major strike-slip faults perpendicular to the margin which appear to have served as accommodation zones during early stretching of the margin. They cut an early generation of dykes. Pseudotachylites, first discovered in 1994 in the Tasiilaq region to the south and recently confirmed to be Tertiary by $^{40}Ar/^{39}Ar$ dating (M. Storey, unpublished DLC data), were found to be common, particularly in association with this strike-slip faulting (Fig. 6). Major normal faults were found to be rare, but low-angle mafic sheets and bed-parallel slip indicate that low angle deformation is significant in the sediments in Sødalen and at Kap Edvard Holm.

Fig. 5. The dyke swarm on Langø giving an impression of the difficulties of working this area.

Sill complexes and macrodykes

The Tertiary sill complex, hitherto almost undocumented, was sampled in a 50 km transect across the Kangerlussuaq sedimentary basin, where numerous sills intrude Cretaceous and Paleocene sediments and lavas. The accumulated thickness exceeds 1000 m. Compositions represented are mainly diabases, with some picrites and ankaramites and a few syenites. They appear to include the earliest volcanism in the region and represent both lower basalts and plateau basalt compositions. Because they show less alteration than many of the lavas they are expected to place important constraints on magma compositions, especially of the lower basalts which are pervasively altered.

Mapping and sampling of macrodykes at Sødalen and Kræmer Ø, which lies just to the west of the Skaergaard intrusion, were also carried out.

Fission track project

In order to quantify the extent and timing of vertical movements in the area, basement gneisses were collected for the separation of apatite. The samples were largely grouped in two major traverses: one parallel to Kangerlussuaq, the other perpendicular to the coast opposite Deception Ø, about 100 km to the south. Samples were taken wherever possible from a range of altitudes from sea level up to about 2000 m, although this was not possible on the southerly traverse. Previous work (Brooks, 1979, 1985; Gleadow & Brooks, 1979) has shown that a major dome structure centred on Kangerlussuaq was probably raised about 50 Ma ago and was succeeded by regional plateau uplift. Larsen (1990) showed this to be part of the regional margin uplift and to be compared with the conjugate European margin (Rohrman *et al.*, 1995). Fission track dating will allow uplift rates and timing to be measured and eval-

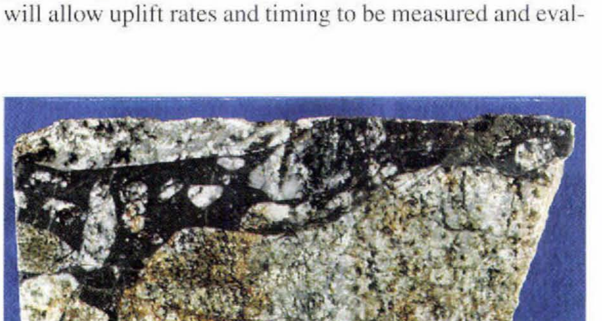

Fig. 6. Hand specimen of pseudotachylite. Sample is about 18 cm long. Photo: J. Lautrup.

uated in the light of break-up events. The implications of the uplift history can be important to understanding the geodynamics of the area (e.g. Larsen & Marcussen, 1992; Lawvers & Müller, 1994).

Gabbroic intrusions

Gabbros are an important part of the oceanic crust and appear to have been intruded in abundance during the Tertiary break-up in East Greenland. The following gabbro intrusions were studied and sampled: Lilloise, Kruuse Fjord and the Imilik complex. Most of these studies were continuations of previous work, including that on the Imilik complex, where both older and younger bodies were identified in 1994. The older gabbros are heavily deformed and intruded by numerous dykes, whereas the younger are undeformed and only cut by the latest dyke generations. Material was collected for $^{40}Ar/^{39}Ar$ radiometric age determinations. The gabbros and other rock types at Lilloise Bjerge are of exceptional interest, as the complex is a very high temperature intrusion, which has not exchanged oxygen with its surroundings (Sheppard *et al.*, 1977) and contains a primordial helium signature (Kelemen *et al.*, 1991). It also lies close to the deduced track of the Icelandic plume centre (Lawvers & Müller, 1994).

Dykes with mantle nodules

Brooks & Rucklidge (1973) described a loose block from Wiedemann Fjord, near the Lilloise intrusion, which contained harzburgite mantle nodules alongside discrete nodules of kaersutite, diopside, salite, grey spinel and opaque spinel. These nodules represent one of the very few examples of such mantle nodules from the entire North Atlantic province and potentially contain valuable information about the nature of the underlying mantle.

In 1995 several N–S trending, nodule-bearing dykes on the eastern side of the head of the fjord and on the outer coast at Kap Ravn (which lies just west of Wiedemann Fjord) were discovered. These dykes are thin (~50 cm wide), but may be followed over long distances. Dyke margins are free of nodules and megacrysts, which are highly concentrated along the centres. The host rock is a kaersutite-rich lamprophyre, similar to many others in the area, and the nodules do not exceed about 3 cm in size. Kaersutite megacrysts are up to 4 cm across. Blocks containing numerous pyroxenite nodules were also found in a somewhat different host rock lithology.

Other activities

As part of the documentation of DLC, and in association with documentation of the Ocean Drilling Progam, filming was carried out by Aaron Woods (ODP, Texas A & M University).

Acknowledgements. The 1995 programme was entirely dependent on the high skills of the helicopter and Twin Otter personnel from Greenlandair A/S and from Flugfélag Norðurlands H/F, Akureyri, respectively. The personnel in the base camp and in particular, Troels Nielsen, DLC, who planned and directed the complex logistic operations, are thanked for constant and efficient support.

Appendix. Personnel involved in various aspects of the work are as follows:
Plateau basalts: A. K. Pedersen, L. M. Larsen W. S. Watt (University of Copenhagen, GEUS and DLC), M. Watt (Bornholms Museum), assisted for part of the time by M. Storey, S. Bernstein, C. Tegner and C. K. Brooks (University of Copenhagen and DLC), D. K. Bird, P. O'Day and P. Neuhoff (Stanford University, USA), and P. Kelemen (Woods Hole Oceanographic Institution, USA). Also present for a shorter period were J. Hopper (DLC), R. A Duncan (Oregon State University, USA) and Johann Helgasson (private consultant, Iceland). Studies of the laterites and zeolites were carried out by P. O'Day and P. Neuhoff, respectively.
Prinsen af Wales Bjerge: C. K. Brooks (University of Copenhagen and DLC), D. Bird, P. Neuhoff and P. O'Day (Stanford University, USA).
Lower basalts: C. E. Lesher, P. Thy and I. Ukstins (University of California, Davis, USA) and H. Hansen (University of Copenhagen and DLC).
Coastal dyke swarms and flexure: K. Hanghøj and M. B. Klausen, (DLC and University of Copenhagen), O. Svenningsen (DLC), J. Karson, D. Curewitz and L. Guenther (Duke University, USA).
Fjord dykes: P. M. Holm and G. Hoffmann Barfod (University of Copenhagen).
Dykes and sill complexes: S. Bernstein and C. Tegner (DLC), R. Wilson (University of Aarhus, Denmark), and P. Momme and P. Gisselø (University of Aarhus).
Gabbros: S. Bernstein and C. Tegner (DLC), D. Bird (Stanford University, USA) and P. Kelemen (Woods Hole Oceanographic Institution, USA).
Fission track sampling: C. K. Brooks (University of Copenhagen and DLC).

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ODP Leg 163, South-East Greenland volcanic rifted margin

Hans Christian Larsen, Robert S. Duncan, James F. Allan and ODP Leg 163 shipboard party

The South-East Greenland margin is a type example of a volcanic rifted margin. The margin is characterised by a broad seaward-dipping reflector sequence (SDRS) composed of basalt that onlaps continental (mainly Precambrian) crust to the west and terminates eastward in oceanic crust of early Tertiary age (Figs 1, 2). In the North-East Atlantic, seafloor-spreading anomalies 24n–24r are the oldest identified pair of anomalies (Talwani & Eldholm, 1977; Srivastava & Tapscott, 1986; Larsen, 1988). Anomaly 24n is developed off South-East Greenland as a double-peaked anomaly, reflecting the three short positive events C24n.1 to C24n.3 and relatively high spreading rates during this interval (approximately 3 cm/yr half-rate; Larsen, 1980).

The minimum age of the South-East Greenland SDRS is constrained by the seaward occurrence of well developed seafloor-spreading anomalies (Fig. 1; Larsen & Jakobsdóttir, 1988). In the north, close to the Iceland-Greenland Ridge, the SDRS extends seaward to chrons C22n–C21n (49–47 Ma). However, most of the South-East Greenland SDRS is found landward of and is older than C24n.1 (53 Ma; Cande & Kent, 1992). Weak and semilinear magnetic anomalies are present over the main SDRS and may represent either low-amplitude anomalies older than C24n (e.g., C25n–C27n, 56–61 Ma) or short magnetic events within C24r (the chryptochrons of Cande & Kent, 1992; see also Larsen *et al.*, 1994a, plate 2, fig. 7).

Evidence for significant magmatism and tectonism during continental breakup is not restricted to the offshore areas. A coast-parallel dyke swarm and associated seaward flexuring of the crust are present from latitude 63°N along the East Greenland coast and northward. Within this zone, gabbroic and syenitic intrusions are present (Fig. 1; Myers, 1980; Myers *et al.*, 1993) and locally associated with basaltic lavas overlying thin sediments (for review see Larsen, 1980; Nielsen *et al.*, 1981; Brooks & Nielsen, 1982). Farther north, a thick and much more extensive flood basalt province is preserved (Fig. 1; Larsen *et al.*, 1989). Comprehensive studies of the onshore region (see also Brooks *et al.*, this report) are being conducted in parallel with Ocean Drilling Program (ODP) drilling and will be augmented in 1996 with a programme of deep crustal seismic imaging that includes the region from the central Iceland Greenland Ridge to south of Greenland (Fig. 1; Larsen *et al.*, 1995; Larsen, this report). In particular, ODP drilling and field geological studies will aim at correlating the onshore and offshore parts of the crustal flexure zone and the volcanic stratigraphy within the two areas.

Drilling was positioned along two margin transects, located distal (Legs 152 and 163) and proximal (Leg 163) to the Iceland plume centre. The two transects were named EG63 and EG66, respectively, in reference to their approximate latitudes. At each transect, drilling was targeted at the pre-rift crust, the breakup unconformity and earliest volcanism, the transition from initial continental volcanism to ocean crust volcanism and, most seaward, a reference hole in steady-state spreading crust. This drilling strategy was designed (Larsen *et al.*, 1991) with two primary objectives: (1) investigation of the development with time along each transect would clarify the progressive weakening of the continental crust and the associated magmatic development; and (2) the study of magmatic development and the magma source at different offsets from the Iceland plume in order to evaluate possible radial zonation in the original plume structure. Additional reference points for the second objective are provided by the earlier Deep Sea Drilling Project (DSDP) Leg 81 drilling at the Hatton Bank (Fig. 1; Joron *et al.*, 1984) and ODP Leg 104 drilling at the Vøring margin (intermediate northern offset; Viereck *et al.*, 1988; see also Larsen *et al.*, 1994a).

Background and operations

Geophysical database

Legs 152 and 163 were planned on the basis of extensive seismic data over the South-East Greenland margin (Fig. 2). The database comprises three different sets of seismic data: (1) regional to detailed grids of shallow, high-resolution multichannel seismic (MCS) data (Larsen *et al.*, 1994b); (2) a regional grid of deep 7 seconds (two way traveltime, TWT) MCS data (Larsen, 1990); and (3) deep 14 seconds (TWT) MCS data (Larsen *et al.*, 1995). In addition, aeromagnetic and regional marine gravity data exist (for a more extensive review and references see Larsen *et al.*, 1994a).

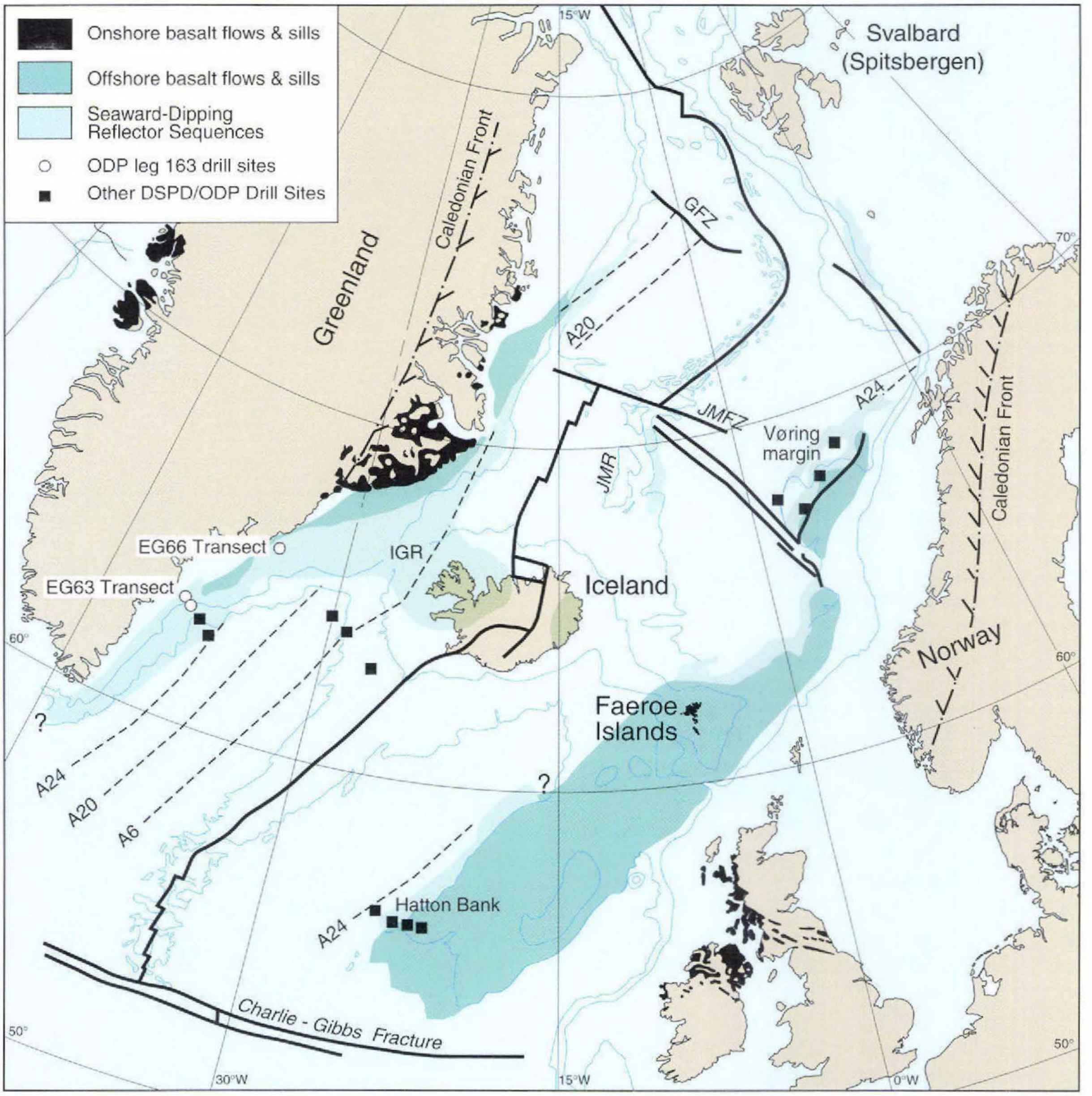

Fig. 1. Geological map of the North Atlantic showing the distribution of seaward dipping reflector sequences, fracture zones (GFZ, JMFZ), ocean floor ridges (JMR) and continental flood basalts of the North Atlantic volcanic province. ODP and DSDP drill sites along the volcanic rifted margins of the North Atlantic are shown. Subaerially erupted basalts show flood basalt structure landward of the inferred continent/ocean boundary and have a SDRS structure seaward of the boundary. IGR: Iceland-Greenland Ridge.

Leg 152: results and implications for Leg 163

A number of important observations made during Leg 152 drilling (EG63 Transect on Fig. 1) into the South-East Greenland SDRS significantly affected the detailed planning of Leg 163. These include the following: (1) the occurrence of highly tilted to subvertical pre-rift sediments below the inner part of the SDRS; (2) that early, continentally hosted and contaminated basaltic to andesitic volcanic rocks of 61–62 Ma age (Sinton *et al.*; 1994) overlie these sediments; (3) that the upper limit of these lower lavas is a sharp transition – possibly a hiatus – into picritic to tholeiitic lavas, followed by basalts of uniform composition that resemble depleted tholeiites from Iceland and appear to make up the main part of the SDRS; and (4) that all recovered igneous units were erupted subaerially. Thus, Leg 152 confirmed that the SDRS is a wedge of predominantly basaltic material extruded subaerially in accord with the

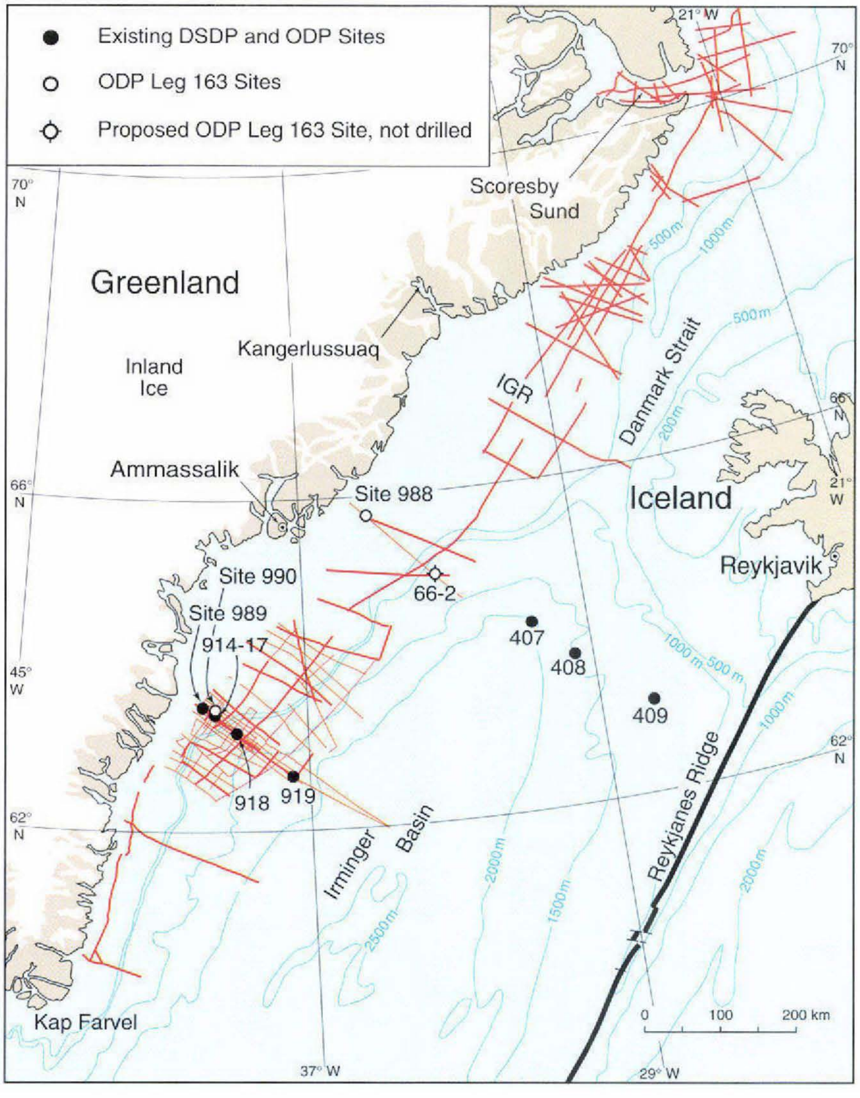

Fig. 2. Seismic track map and regional bathymetry. Previously drilled holes and Leg 163 drilled sites and planned sites are shown. IGR: Iceland-Greenland Ridge.

model for crustal accretion in Iceland (Pálmason, 1986) and with the interpretation of seismic data (Mutter *et al.*, 1982; Larsen & Jakobsdóttir, 1988).

The findings during Leg 152 imply the presence of a rapid transition from continental to oceanic crust below the inner part of the SDRS. During formation of this continent to ocean transition, pre-rift sediments were deposited in a basin of unknown width and, later, in a zone close to the final line of breakup, subjected to faulting and crustal extension, uplift and erosion prior to volcanism (see also Larsen *et al.*, 1994a).

The Leg 152 data are not adequate in a number of aspects: suitable material for age determination of the oceanic succession (i.e. the main part of the SDRS) is lacking, the sampling of the transition from initial picritic to depleted tholeiitic volcanism within the oceanic succession is non-continuous, and the oldest part of the continental volcanic succession has not been recovered. In addition, the pre-rift sediments were poorly sampled because of their subvertical orientation, and they have been too strongly metamorphosed to yield any age-diagnostic microfossils or palynomorphs.

Leg 163 was planned to overcome these deficiencies within the southern EG63 transect, as well as to sample the break-up and early seafloor spreading volcanism in a more proximal position to the proposed Iceland 'hot spot' track along the northern EG66 transect. The faint signature of the Iceland plume in the Leg 152 rocks suggests that a stronger plume imprint could be present at this location closer to the former plume axis, which if true, would indicate a radial zonation within the original plume structure.

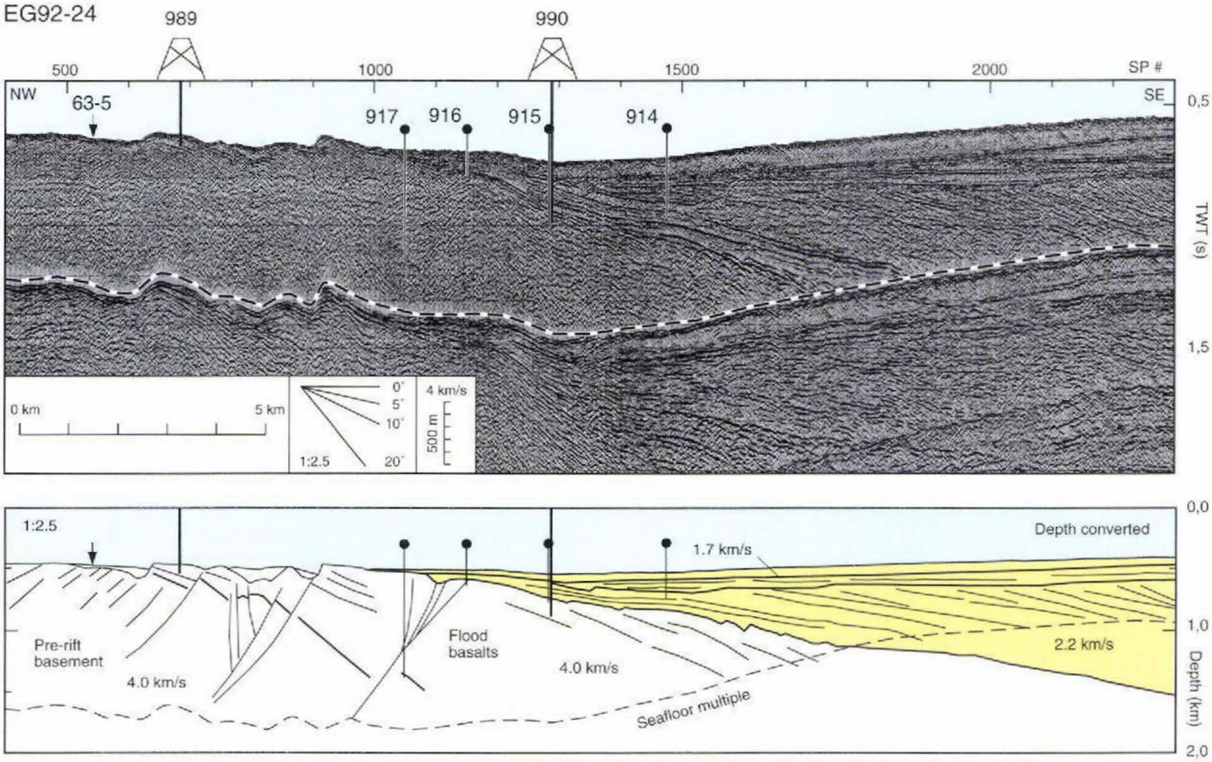

Fig. 3. Seismic cross-section through Site 989 (top). Interpretations shown in line drawing (middle) and migrated interpretation (bottom). Steeply dipping to subvertical pre-rift sediments were encountered within the rotated fault block located below the lava sequence at Site 917. ODP Sites 914–917 are described in Larsen *et al.* (1994a). Planned Site EG63-5 designed to sample the pre-rift crust (sediments?) was not drilled.

Integration of observations from drilling, field geology, and geophysics on crustal structure and deformation, timing of volcanism and the involvement of Iceland plume material in the break-up process, will eventually enable a critical review of current models of plume structure and the impact of mantle plumes on the process of continental break-up (e.g., Mutter *et al.*, 1988; White & McKenzie, 1989; Richards *et al.*, 1989; Campbell & Griffiths, 1990; Coffin & Eldholm, 1992; Kent *et al.*, 1992; Holbrook & Keleman, 1993).

Drilling plan

In order to meet the main objectives, six first-priority sites were planned for the two transects. Three sites were planned for the innermost part of the EG63 transect. Two sites were targeted to increase the sampling of the pre-rift crust and oldest volcanic cover, and one site was to deepen Site 915 in order to provide stratigraphic overlap with Site 917 (Figs 2, 3). Three sites were also planned for the northern EG66 transect (Figs 2, 4). The two sites within the innermost part had objectives roughly similar to the inner sites of the EG63 transect, although less ambitious in terms of stratigraphic coverage. The additional seaward site was planned in SDRS-type oceanic crust of anomaly 22 age (i.e. in steady-state accreting Icelandic-type oceanic crust). Along the EG66 Transect already existing DSDP Sites 406–408 (Fig. 2) would extend the transect into Miocene and younger ocean crust.

Operations and changes in the drilling plan imposed by drilling problems and weather

The cruise started from Reykjavik on 7 September 1995 and was scheduled to end in Halifax, 27 October. However, early in the cruise the drill-rig was damaged during shallow water coring, and later in the cruise extreme storm conditions damaged the ship and forced an early termination of the cruise. As a result of these events the scientific drilling operations at Leg 163 were reduced to less than one-half of the planned programme.

Recoil from a break in the drill pipe on 10 September damaged the top-drive assembly after only one day of drilling at the first, shallow-water site at the northern EG66 Transect (Site 988; Figs 2, 4). A port call to Reykjavik, Iceland, was made in order to make the necessary re-

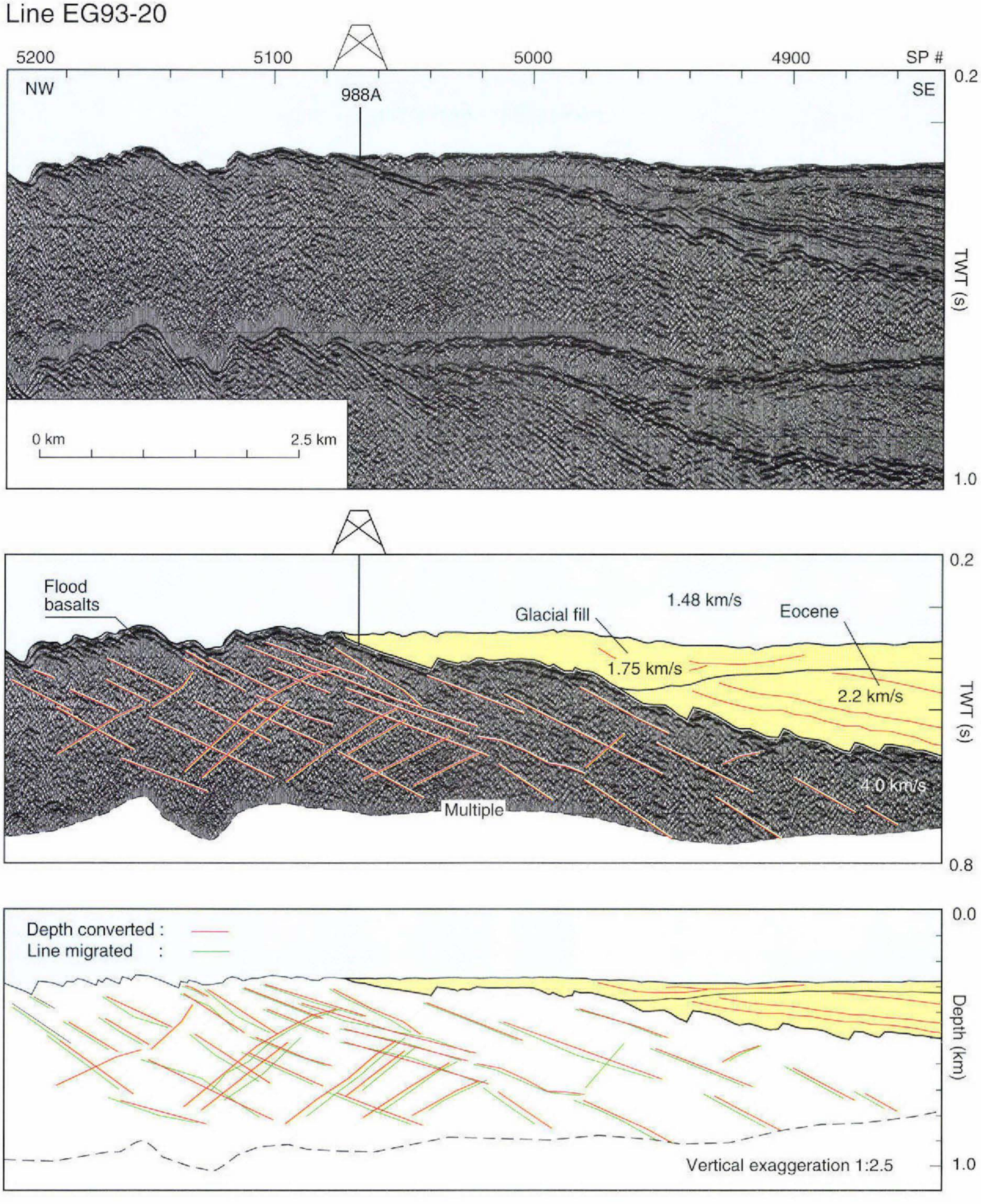

Fig. 4. Seismic cross-section (top) through Site 988 at the EG66 transect. Interpretations shown in line drawing (middle) and migrated section (bottom). The Eocene age of the post-rift sediments is inferred by correlation with the EG63 transect (Larsen *et al.*, 1994a). Two more sites were planned for this transect (landward and seaward of Site 988; not shown), but were not drilled.

Fig. 5. View from the bridge of the drill ship *JOIDES Resolution* during the hurricane on 30 September 1995. Bridge level is at approximately 10 m height. The waves were estimated to be at least 20 m high, and shore based analysis of video-tapes suggested that some waves approached 30 m height.

pairs. Permission to drill in water depths shallower than 300 m was temporarily withdrawn by the operator of ODP, Texas A&M University, pending review of safety procedures and the delivery of supplementary drilling hardware. Operations therefore resumed at the deeper water sites along the southern EG63 transect on 16 September. Drilling progressed (Sites 989 and 990; Fig. 3), with interruptions due to heavy seas and icebergs drifting across the drill sites, until 29 September.

Extreme hurricane conditions built up rapidly through the night of 29 September. At this time Site 990 was almost drilled to target depth, and preparations for re-occupying and deepening Site 989 were made. However, the wind speed continued to increase and at many times it exceeded 100 knots from north-north-east, and remained at hurricane force for at least 26 hours (extra-tropical hurricane force 2). By the morning of 30 September, the ship was being battered by steep short-period waves, more than 20 m high, and she was unable to maintain position without risking severe damage (Fig. 5). The ship's bridge took water through a broken window, which caused both radars to fail and threatened the computers controlling the dynamic-positioning system. Numerous thrusters were mechanically damaged or became inoperable because of flooding. In spite of reduced maneuverability, the ship was able to maintain heading in the wind and sea while being forced southwards at a speed of up to 4 knots with an increased potential of colliding with icebergs. When the storm abated to gale force on 1October, the ship turned southwards *en route* to Halifax, Nova Scotia, for repairs. As a result of these untimely events, only three of the planned six sites were drilled.

Drilling results

Site 988

Site 988 is located 56 km east of the East Greenland coast, within the northern drilling transect EG66 (Figs 2, 4). The site was selected to penetrate deeply into the feather-edge of the SDRS that overlies the transition zone between continent and ocean crust. The primary drilling objectives at this site were to determine the composition, age and eruption environment of the SDRS in a position close to the Iceland-Greenland Ridge for comparison with the distal SDRS cored during Leg 152. Hole 988A was drilled in this location, but only to shallow depth (32 m below seafloor; mbsf) where the drill-pipe became stuck and broke.

A thin layer (0–10 mbsf) of Quaternary (?) glaciomarine sediments unconformably overlie basaltic basement (igneous units 1 and 2). The glaciomarine sediments include rounded cobbles of gabbro, fine-grained granite, aphyric basalt, and gneiss. Compacted diamicton was not recovered at this site.

Two igneous flow units were recognised in the core recovered from the interval 10–32 mbsf. Igneous unit 1 is a plagioclase-pyroxene-olivine-phyric basalt. Only the lower contact was recovered; the thickness of the unit is between 19 and 21 m. The unit has a massive aspect, is sparsely vesicular and shows alteration of the glassy groundmass and the sparse olivine phenocrysts. Igneous unit 2 (29–32 mbsf) is, by contrast, highly to completely altered.

Shipboard X-ray fluorescence (XRF) data show that both units have high Nb/Zr (0.12) and Ce/Y (1.2) ratios, identical to Tertiary basalts from Iceland (Fig. 6). The low Ni content and low Mg# of igneous unit 1 (about 74 ppm and 0.50, respectively) are consistent with the evolved three-phase phenocryst assemblage of this basalt. Both units were most likely emplaced as lava flows, but the absence of an upper contact in Unit 1 means that we cannot eliminate the remote possibility that it is a sill. The highly oxidised aspect of unit 2 is consistent with emplacement as a flow in a subaerial environment.

The relative enrichment in incompatible elements seen at Site 988 (Fig. 6) is consistent with the pattern of enrichment along the present day Reykjanes Ridge (Schilling, 1982) and within late Tertiary ocean crust south of Iceland (DSDP sites 406-408; see Fig.2)

Palaeomagnetic data for basalts at Site 988 were obtained using the shipboard cryogenic magnetometer. The core has a consistent reversed polarity with two exceptions. One normal polarity reading was probably caused by two pieces of core being inverted during labelling and splitting. Another interval of normal polarity is located in the highly altered clay-rich flow top material of unit 2 immediately below the bottom of igneous unit 1. The magnetic orientation of this material was probably affected by the high degree of secondary alteration observed, or possibly by the drilling process.

Site 989

Site 989 is located about 40 km east of the East Greenland coast. It is one of the three drill sites planned for the southern drilling transect EG63 (Figs 2, 3). Drilling at Leg 152, Sites 915 and 917, penetrated a thick lava sequence that recorded development from early continental lithosphere (crust?)-contaminated volcanism, through transitional picritic and tholeiitic volcanism contemporaneous with break-up, into oceanic volcanism. Site 989 was selected to penetrate and sample the very oldest lavas of the SDRSs that overlie the breakup unconformity and underlying, layered pre-rift crust, possibly pre-rift sediments. The primary drilling objectives at this site were: (1) to determine the stratigraphy, composition, age, and eruption environment of the volcanic rocks above the break-up unconformity; (2) to determine the nature and age of the break-up unconformity; and (3) to determine the nature and deformation of the continental basement and/or pre-rift sediments beneath the volcanic sequence. Two holes, 989A and B were drilled at this location.

A thin layer (0–4 mbsf) of Quaternary(?) glaciomarine sediments unconformably overlies the basaltic basement (igneous units 1 and 2). The only material recovered consists of discrete rock fragments, including gneiss, aphyric basalts/metabasalts, quartzite and dolerite; fine-grained sediments were not recovered. The relatively easy penetration of the sediments at Site 989 suggests that these are glaciomarine deposits, rather than overcompacted glacial tills.

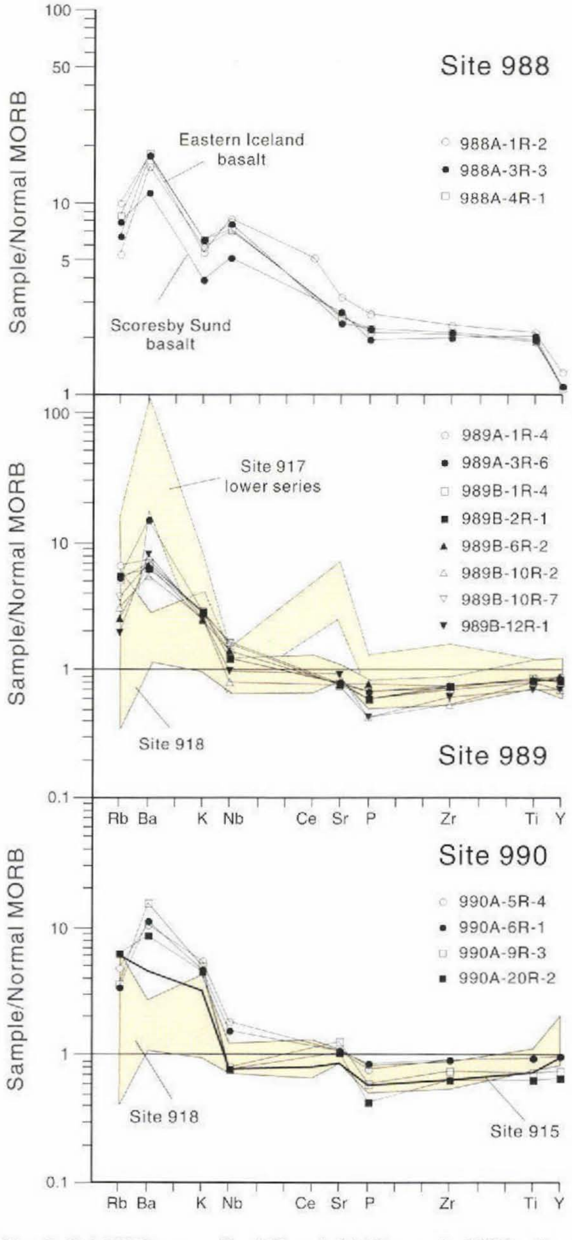

Fig. 6. N-MORB normalised (Sun & McDonough, 1989) minor-element and trace-element spidergrams of cored basalts from the SDRS along the EG66 transects (Site 988) and EG63 (Sites 915, 917, 918, 989, and 990). The Site 917 data include only samples with 6%–9% MgO; samples with high Nb/Zr were excluded. The fields for basalts from Sites 917 and 918 are based on data in Larsen *et al.* (1994a) and Fitton *et al.* (in press). The Site 988 lavas are similar to Tertiary basalts from Iceland and Scoresby Sund, East Greenland (Larsen *et al.*, 1989; Fitton *et al.*, in press) and are considerably enriched in incompatible elements compared to the lavas the EG63 transect.

Two igneous flow units were recognised in the core recovered from the interval 4–84 mbsf (Hole 989B). From seismic data, these are indicated to lie stratigraphically below the lavas drilled at Site 917 and represent the oldest part of the SDRS.

Igneous unit 1 is at least 69 m thick, the thickest lava flow yet reported from a SDRS. The top of the flow was not recovered. Unit 1 is essentially aphyric. The groundmass consists of plagioclase, augite, magnetite, trace olivine and mesostasis. Clay alteration is total for both mesostasis and olivines, whereas plagioclases and augites are generally fresh. It is characterised by uniform grain size, uniform vesicularity, high mesostasis content and repeated bands showing quench textures. These features indicate rapid cooling during solidification throughout emplacement of the entire lava flow. Unit 1 is interpreted as a compound lava flow consisting of numerous individual sub-units 0.1–10 m thick. The large number of thin sub-units, together with the absence of sharp flow contacts, may indicate both proximity to the eruptive vent and rapid eruption of the entire lava flow. An upward decrease in the maximum sub-unit thickness within igneous unit 1 may reflect diminishing eruption rate with time during deposition of this large flow.

Igneous unit 2 is at least 11 m thick, but the lower boundary was not penetrated. It is very massive, porphyritic with phenocrysts of plagioclase, augite, and trace olivine in a very fine-grained matrix. Olivine phenocrysts occur as individual disseminated grains that are now totally altered to clay. Plagioclase and augite phenocrysts are fresh, commonly strongly zoned and resorbed (plagioclase), and in glomerocrystic clusters.

The two igneous units recovered at Site 989 are both strongly depleted in a number of incompatible elements such as Zr, Nb, Ti and P and presumably derived from a depleted mantle source (Fig. 6). Both lava flows are composed of evolved basalt, which implies storage in a magma chamber underlying this part of the volcanic succession. Similar crustal magma chambers were invoked for the lavas in the Lower Series at Site 917, but these are enriched in Sr and Ba, probably because of assimilation of a crustal component (Larsen *et al.*, 1994a; Fitton *et al.*, in press). The low Sr and Ba contents in the Site 989 lavas preclude a direct correlation with the lower series in Site 917 located only 4 km in down-dip direction.

Unit 1 recovered in both sites 988 and 989 appears to carry a normal magnetic polarity. If confirmed, this will be the first flow of normal polarity reported from the East Greenland margin. Unit 2 appears to contain both normal (top) and reversed magnetic polarity. The top part of the flow was possibly remagnetised during the emplacement of the normally magnetised unit 1. Confirmation of the magnetic polarity must await further alternating field and thermal demagnetisation studies.

Site 990

Site 990 is located about 50 km east of the East Greenland coast, within the southern drilling transect EG63. It was one of three drill sites planned to complete the stratigraphic sampling of the earliest volcanism along this margin (Figs 2, 3). The site was located at the position of previous ODP Site 915 in order to penetrate more deeply into the lava succession (only one lava flow unit was recovered in Hole 915A). By expanded stratigraphic sampling it would be possible to test the hypothesis that Iceland-type oceanic crustal accretion and steady-state production of Iceland-type tholeiites were initiated within this stratigraphic interval as indicated by the Hole 915 lava. Another important objective at this site was to sample material suitable for precise radiometric and magnetostratigraphic age determination in order to assess the length of a suspected hiatus in volcanic activity located between the middle and upper series lavas at Site 917. One hole, Hole 990A was drilled very close to Site 915 to a total depth of 325 mbsf.

Because the sedimentary section had been cored at Site 915 during Leg 152, Site 990 was washed to a depth of 182.0 mbsf and rotary cored below that level. Sediments were recovered in the interval 182.0–202.3 mbsf and subdivided into two lithologic units termed lithologic unit I and lithologic unit II. The ages of these are unknown, but the ages of the overlying sediment and underlying basalt at Site 915 suggest an early Eocene age (Larsen *et al.*, 1994a).

Lithologic unit I is a calcite-cemented mixed-cobble conglomerate, dominated by clasts of altered basalt, gabbro, and dolerite; quartzite and siliciclastic siltstone form the remainder of the cobbles. The cobbles are generally rounded to well rounded and range in size from 4 to >12 cm in diameter. The matrix is a poorly sorted silty sand, with angular grains, sand-sized mudstone intraclasts and calcite cement.

Lithologic unit II directly overlies basalt and is a clayey volcaniclastic breccia, dominated by basaltic debris. Clasts in the breccia are predominantly angular and composed of dark yellowish brown, altered basaltic material. The sedimentological data suggests that unit I was deposited in a high-energy environment, possibly a high-gradient stream, a shallow, wave-influenced marine setting or a fan delta.

Additional sedimentary material, apparently not transported, was recognised as red, brecciated to clayey material on the tops of flow units within the basalt basement.

Thirteen volcanic flow units were recognised below the sedimentary units and down to 325 mbsf. Flows were identified on the basis of changes in phenocryst assemblage or the presence of weathered or vesicular flow tops. Lava flows fall into one of three types: aa, pahoehoe, and transitional. Pahoehoe flows dominate in the lower part of the drilled sequence, whereas aa flows are ubiquitous in the upper portion. The top of the volcanic section at this site (and the previously drilled Site 915) is deeply weathered and oxidised, indicating that eruption occurred subaerially with some time gap between successive flow units.

Flow units cored at Site 990 range from aphyric to highly olivine or plagioclase-olivine-clinopyroxene-phyric basalt. The olivine content decreases upwards in the section, whereas both grain size and flow thickness increase upwards. There is a subtle but systematic compositional variation in trace-element content from the base to the top of the sequence (i.e. decreasing Cr and Ni and increasing V, Nb, Zr and Y). In general, the lavas are moderately evolved with low trace-element abundances, and are geochemically similar to the single unit recovered from Site 915 and all units at Site 918 (72 km to the east; Fig. 6). Lavas similar to the upper series cored at Site 917 (3 km to the west) were not found, indicating that the transition from the break-up related series to the Iceland-type tholeiitic series that dominates the oceanic SDRS is abrupt and occurs over a stratigraphic interval of <100 m (seismic correlation in Fig. 3).

Palaeomagnetic data for the basalts from Site 990 suggests the presence of a magnetic reversal between two normally magnetised flows at the top of the drilled section and the lower 11 reversely magnetised flows. This finding of a magnetic reversal may have significant chronostratigraphic importance and needs confirmation by onshore laboratory work.

Conclusions

Despite the significant loss of operational time because of drilling problems, weather conditions and consequent ship damage, extraordinary high recovery of core at three critical sites provided the material to address several of the high-priority objectives of the leg. However, the main tectonic objective of drilling through the break-up unconformity and sampling the pre-rift crust (presumably sediments) was not fulfilled. Likewise, the important objective of extensive sampling of the rift volcanism close to the Iceland hot spot track (EG66 transect) was only very briefly addressed. The following are the initial, major results of the cruise:

- A virtually complete record of the volcanic evolution of the East Greenland margin at latitude 63°N now exists. This includes the earliest, depleted and continentally contaminated, relatively deeply segregated magmas, through break-up related picritic and tholeiitic magmas derived by shallower and larger degrees of melting, to a steady-state oceanic magma series.
- Two magnetic polarity reversals, the first ever recorded from early Tertiary age volcanic materials of East Greenland, have been preliminary identified; in addition fresh, feldspar-phyric flow units suitable for radiometric dating have been recovered. These findings offer the promise of a detailed and precise time scale for the volcanic activity during break-up.
- The geochemical data indicate that Iceland mantle plume component is more strongly expressed in the compositions of basalts at latitude 66°N compared with 63°N. Together with evidence from DSDP Leg 81 (Hatton Bank, Rockall Plateau) and ODP Leg 104 (Vøring Plateau), significant information on the basic compositional structure of the mantle melting regime that existed during the initiation of the Iceland plume and break-up of the North Atlantic has now been collected.

Acknowledgements. The crew on board the ODP drill ship *JOIDES Resolution* is thanked for outstanding committment to scientific drilling and for professional seamanship during the extreme weather conditions encountered during ODP Leg 163. The site survey for ODP Leg 163 was funded by the Danish Natural Research Council.

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Newsletters and Reports: a service to industry

Martin Sønderholm

Since the beginning of the 1990s the Geological Survey of Greenland (GGU) has provided the petroleum and mining industries with up-to-date information on geological, expeditionary and legislatory matters via the newsletters *Ghexis* (Greenland **H**ydrocarbon **Ex**ploration **I**nformation **S**ervice, since 1990) and *Minex* (Greenland **Min**eral **Ex**ploration Newsletter, since 1992). These newsletters will continue to be published by the Geological Survey of Denmark and Greenland (GEUS) and are available free of charge.

The *Open File Series* was introduced by GGU in 1989 in order to comply with the growing need for making preliminary field data and analytical data quickly available to the public, and especially to industry. The series comprises unedited reports and maps produced in limited numbers and is a key to new developments in the field of economic geology. The reports are based on data collected by the Survey as well as the commercial sector.

By the end of 1995 the series encompassed 83 reports, of which 71 are of direct interest to the exploration community. Those reports related to Greenland mineral exploration published before 1993 have been reviewed in an earlier volume of *Report of Activities* (Schønwandt, 1993); this paper continues that review and includes all *Open File* reports related to petroleum exploration. A total of 41 reports have been released since 1993 of which 35 are of particular interest to industry. These can be divided into four groups by subject, and references will be given below (see also Fig. 1).

- *Geochemistry reports* discuss in general the <0.1 mm fraction of stream sediments
- *Reconnaissance exploration reports* include maps and geochemical analyses coupled with a brief description of the mineral occurrences. Geophysical reports are also found in this category.
- *Review reports* present accounts that range from mines through exploration targets to regional accounts on a single mineral commodity.
- *Petroleum geological reports* include all presently released reports dealing with data resulting from petroleum geological projects.

The type of data represented in the *Open File Series* will from 1996 appear as *Reports* published by the Geological Survey of Denmark and Greenland. A full list of the volumes in the previous *Open File Series* can be obtained from the Survey's *List of Publications* which can be ordered free of charge.

Geochemistry reports

Steenfelt, A., Dam, E. & Nielsen, J. P. 1993: Reconnaissance geochemical mapping of map sheets 67 V.1 and 68 V.1 (66° to 68°N, 51°40' to 54°W), West Greenland. *Open File Ser. Grønlands geol. Unders.* **93/1**, 18 pp.

Steenfelt, A. 1993: Stream sediment geochemical evidence for gold mineralisation in Hudson Land (73°10' to 74°25'N, 21°30' to 24°45'W), North-East Greenland. *Open File Ser. Grønlands geol. Unders.* **93/4**, 25 pp.

Steenfelt, A., Dam, E. & Petersen, A. 1994: Reconnaissance geochemical mapping of the Paamiut region (61°25' to 62°45'N, 48°00' to 50°00' W), South-West Greenland. *Open File Ser. Grønlands geol. Unders.* **94/1**, 16 pp.

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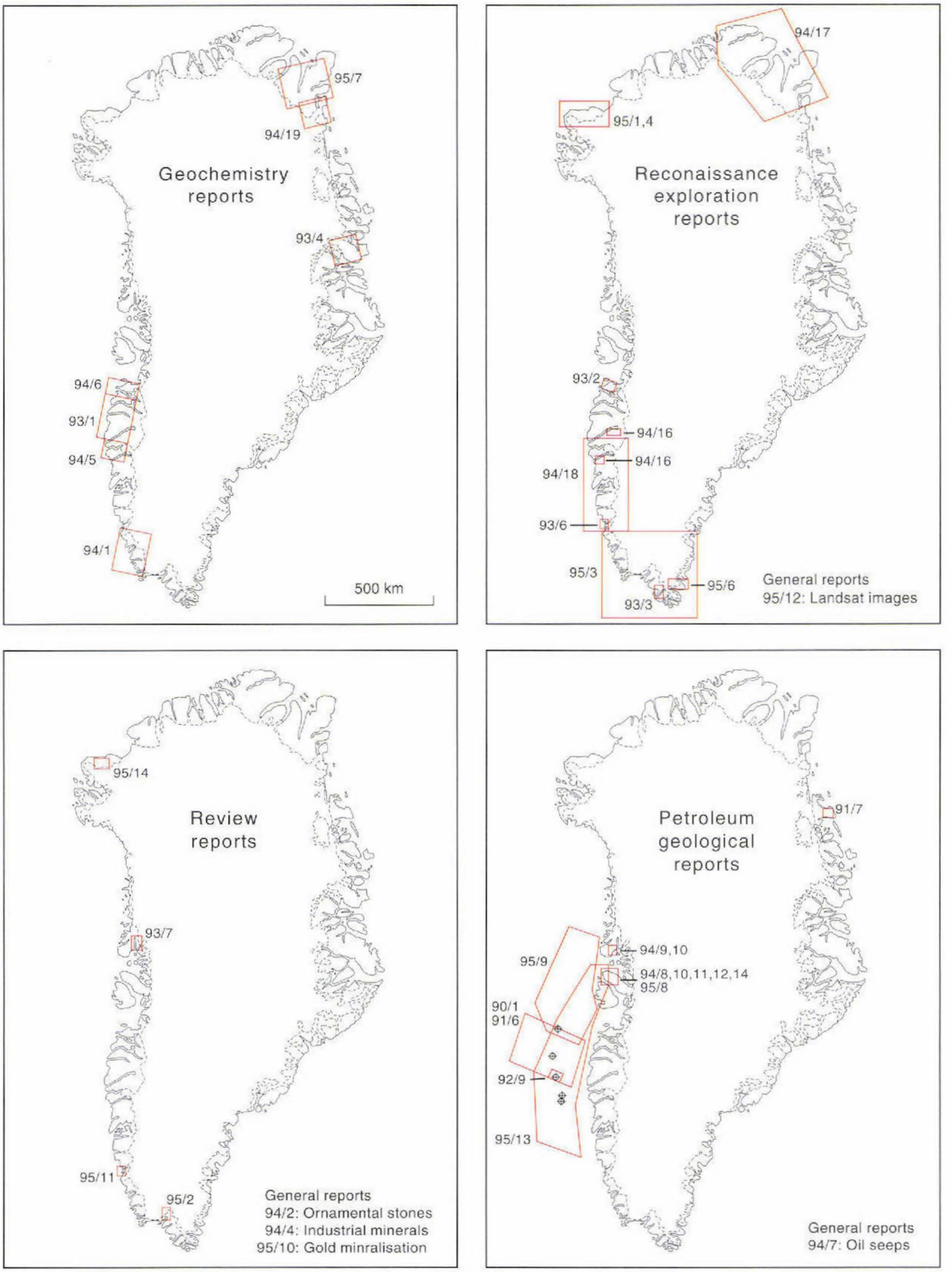

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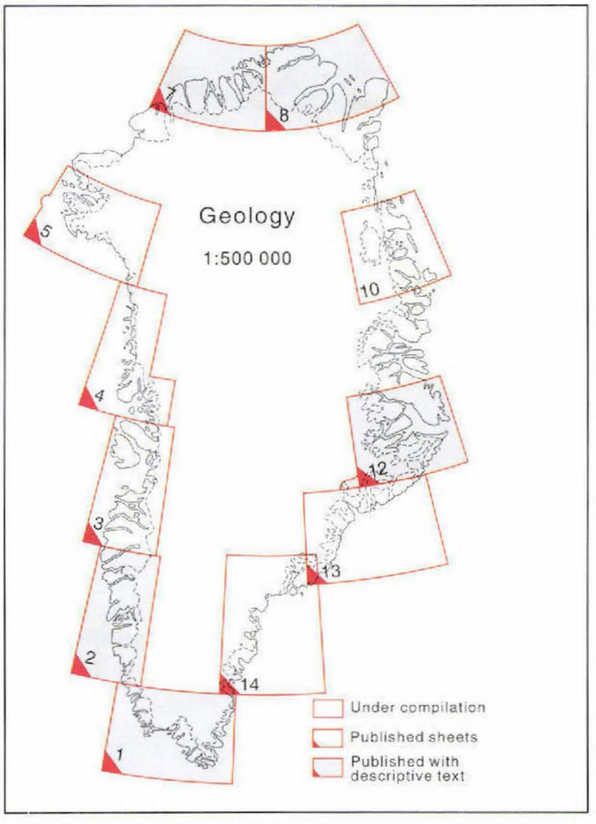
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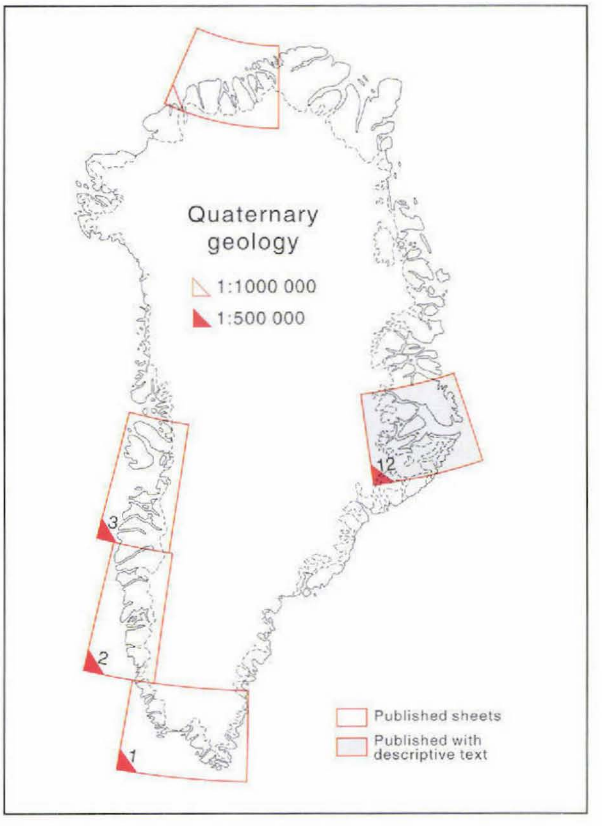
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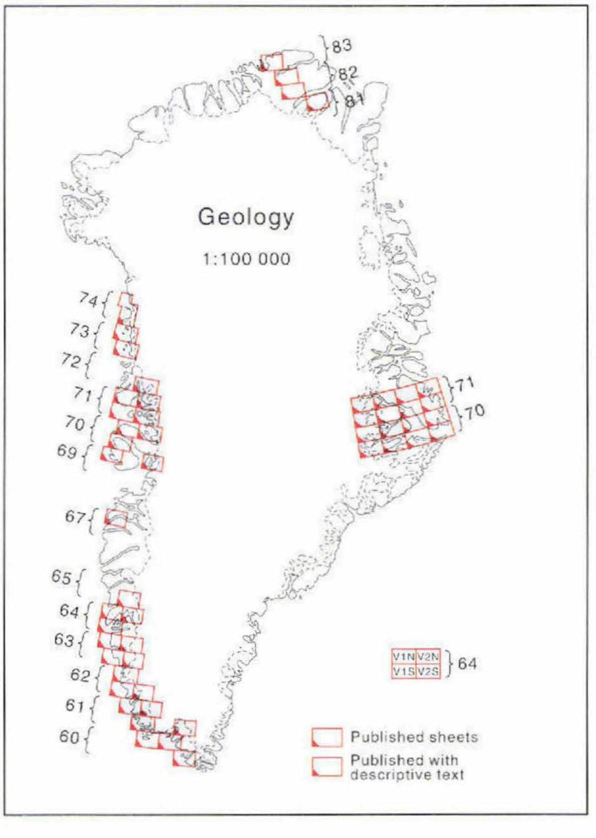
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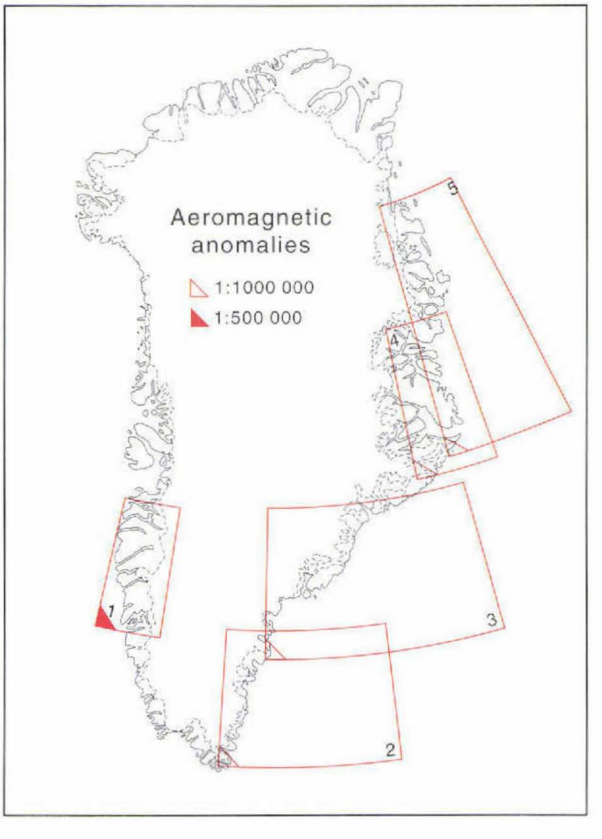
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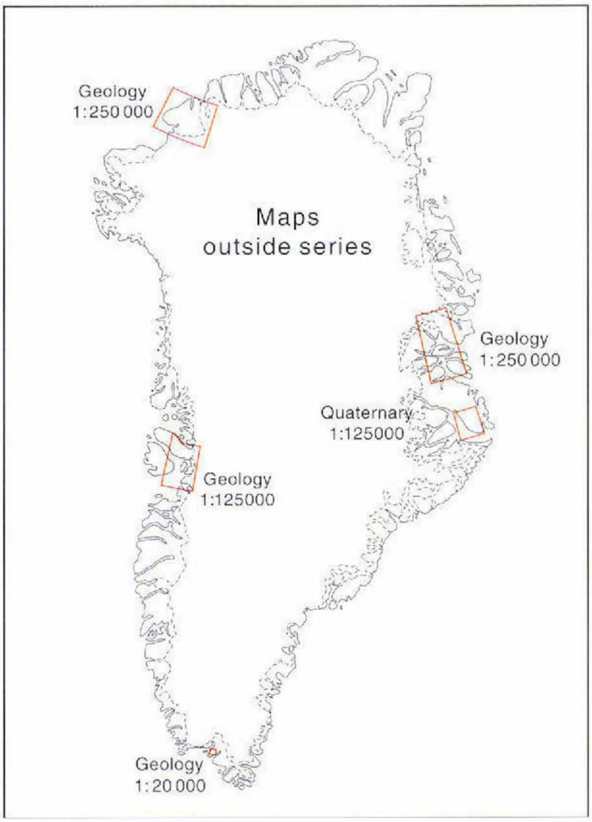

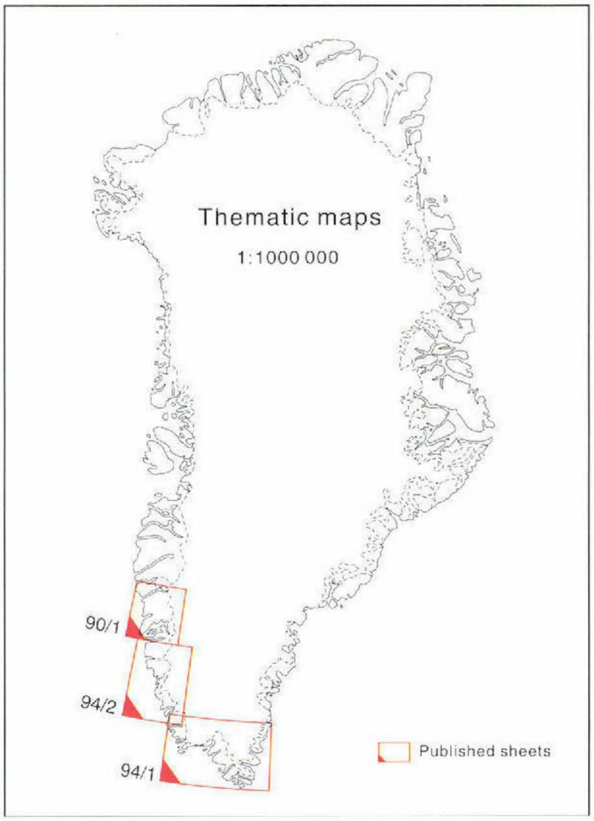

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