DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/62

History of petroleum exploration and summary of potential petroleum basins in Greenland

T.C.R. Pulvertaft

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/62

History of petroleum exploration and summary of potential petroleum basins in Greenland

T. C. R. Pulvertaft

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

Contents

History of exploration

The search for hydrocarbons in the Arctic began in the 1930s and intensified in the 1960s, but it was not until the discovery of the Prudhoe Bay oil field in northern Alaska in 1968 that the potential of the region was finally proved. This discovery stimulated increased exploration throughout the North American Arctic, and in 1969 it was the turn of Greenland to attract serious interest from the oil industry.

West Greenland – the 1970s

The southern and central West Greenland shelf

The first phase of industry activity in Greenland was concentrated in the west, for two reasons: 1) the continental shelf between 63°N and 70°N off West Greenland is the area offshore Greenland where physical conditions, in particular ice conditions, are least inimical to petroleum exploration; 2) in the Disko–Nuussuaq–Svartenhuk area, onshore central West Greenland, there are considerable thicknesses of Cretaceous–Tertiary fluvio-deltaic and prodelta marine sediments that not only have a petroleum potential in their own right but also provide an analogue to what can be expected to occur in the shelf offshore. Some early interest was also shown in North Greenland, where Cambro-Silurian carbonates and mudstones attracted the attention of explorationists from 1969 to 1972; in addition to field geological studies, an aeromagnetic survey was flown over part of the area in 1971.

Exploration on the central and southern West Greenland shelf began with extensive seismic, magnetic and gravity surveys in the period 1969–74, all of which were undertaken under the terms of non-exclusive prospecting licences. Almost 21 000 km of reflection seismic data were acquired during this phase. On the basis of these data, three areas were chosen to be opened for licensing, and companies were invited to submit applications by 15 October 1974. 22 companies responded to the invitation, and in April 1975 exclusive licences were awarded to six groups comprising in all 19 foreign companies and one Danish consortium. The concessions covered 46 blocks with a total area of 19 082 km^2.

In the following four seasons a further 16 000 km reflection seismic data were acquired, and in 1976–77 five exploration wells were drilled (Table 1; Fig. 1). All five wells were declared dry, but in one of them, Kangâmiut-1, a gas kick was taken, the gas being moderately wet (gas components up to C4).

In 1977 the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) acquired a number of very widely spaced seismic traverse and tie lines in the Labrador Sea. These lines did not attract any attention from explorationists at the time, but after reprocessing by GGU[1] in 1989–90 they revealed many tilted fault blocks in deep water areas off southern West Greenland, indicating that these areas had a hitherto unexpected petroleum potential (see later).

[1] GGU = Grønlands Geologiske Undersøgelse, in English the Geological Survey of Greenland. In 1995 this survey was amalgamated with the Geological Survey of Denmark to form the Geological Survey of Denmark and Greenland with the call name GEUS.

Table 1. *Summary of exploration wells drilled offshore West Greenland*

Well	Operator	Date	Location	Water depth	Well depth below sea level	Age and lithology at TD
Kangâmiut-1	Total	1976	66°09′N, 56°11′W	180 m	3862 m	Precambrian basement
Hellefisk-1	ARCO	1977	67°53′N, 56°44′W	163 m	3189 m	Paleocene(?) basalt
Ikermiut-1	Chevron	1977	66°56′N, 56°35′W	447 m	3607 m	Campanian mud-stone
Nukik-2	Mobil	1977	65°38′N, 54°46′W	117 m	2670 m	Basalt, age uncer-tain
Nukik-1	Mobil	1977	65°32′N, 54°46′W	104 m	2339 m	Precambrian basement

The disappointing results of drilling had an immediate effect on companies' activities in the area. Apart from one small seismic survey, no exploration was carried out in 1978, and by the end of the year all concessions had been relinquished. However, there are three important points that should be taken into account when evaluating the experience gained from exploration offshore West Greenland in the 1970s:

1) The area is a high cost frontier area, and companies calculated that in this environment only very large hydrocarbon reservoirs would be commercially viable. Sufficiently large structures to host these reserves were not seen in the seismic data from the 1970s, but *have since been found in deeper water areas which were not covered by the early seismic surveys.*

2) Experience showed that in the summer, exploration can be carried out off West Greenland with very little inconvenience caused by ice. At none of the five well sites did drilling have to be suspended due to the threat of icebergs, although at one well the rig would have had to have moved off site had it not been about to terminate drilling anyway.

3) With hindsight it can be seen that four of the five wells did not penetrate structures that could ever have been traps for hydrocarbons, however much had been generated in the area. Either there was no seal over reservoir formation, or there was no reservoir formation in the structure tested. Only one well, Kangâmiut-1, tested a potential trap, and even this is flawed, in that it is bounded on one side by a potentially leaking fault. Interestingly enough, Kangâmiut-1 was the only well that *did* find traces of hydrocarbons (moderately wet gas with components up to C4). The drill stem test reported only water, but this water was almost certainly that of the drilling mud. To control the gas kick the specific gravity of the mud had to be raised, so that it invaded the tested formation and was then recovered in the test.

Melville Bay

In the period 1966–1971 the Geological Survey of Canada and its affiliate the Bedford Institute of Oceanography carried out airborne magnetic and shipborne magnetic, gravity and refraction seismic surveys in Baffin Bay. The primary aim of these surveys was to answer fundamental questions about Baffin Bay such as whether it is a small oceanic basin or an intracontinental rift and whether the surrounding shelf areas are underlain by thick sedimentary wedges like those recorded along many other continental margins. The results indicated clearly that the deep, central part of the bay is underlain by sediments up to at least 4 km thick and that these lie on a thin oceanic crust. In addition, evidence in the form of aeromagnetic anomaly patterns and a striking negative gravity anomaly suggested the presence of a deep graben under Melville Bay with a sedimentary fill more than 10 km thick. That such a basin could have a considerable petroleum potential was obvious, and a major oil company proposed a seismic programme in Melville Bay in 1980. However, this came to nothing, and it was not until 1992 that a reconnaissance reflection seismic survey was carried out in the area as part of the KANUMAS project (see later).

Offshore East Greenland 1979–82: the NAD project

With the discovery of several giant oil fields in the northern North Sea, attention became directed to areas that had been contiguous with northern North Sea and west Norwegian shelf before the opening of the North Atlantic; one of these areas was offshore East Greenland.

In 1978 the Danish Energy Authority (now part of the Ministry of Environment and Energy) granted funds for an aeromagnetic survey of a major part of the East Greenland shelf (Project EASTMAR). In the following year funding was granted by the European Community to expand the project to include a marine geophysical survey, and the entire programme was named the NAD project (North Atlantic D).

Prior to the NAD project some seismic data had been acquired by BGR in 1975 and 1976 in the area north of 67°N, and south of 68°N the Centre National Exploration des Oceans (CNEXO) acquired almost 4900 km of seismic data in 1977. Interpretation of the relevant parts of these data was incorporated in the Final Report of the NAD project (1985).

The EASTMAR survey was carried out in 1979, and a total of 63 219 km were flown covering the East Greenland shelf from 60°N to 78°N. Until the KANUMAS survey (see later) these data were the only geophysical data acquired systematically over the East Greenland shelf north of 73°N. The seismic part of the NAD project was carried out in 1980–82, during which years 7793 km line km were acquired in the area between 62°30′N and 73°N (Fig. 2).

The results of the NAD project showed that south of 70°N only Tertiary plays could be expected, as widespread, thick Tertiary basalts covered any potential Mesozoic plays which in any case were likely to be overmature. On the other hand the northern part of the project area appeared on the basis of the limited data available to be highly prospective. It was partly the results of the NAD project that inspired the KANUMAS project.

Jameson Land Basin – ARCO exploration 1984–90

As petroleum exploration on the west Norwegian shelf progressed, interest was not only directed to offshore East Greenland but also to onshore areas between 70°N and 75°N. Here there are extensive, thick Upper Palaeozoic and Mesozoic sedimentary successions that are analogues of successions known from drilling in the northern North Sea, the west Norwegian shelf and the Barents Sea. The largest single basin onshore East Greenland is the Jameson Land Basin, and it was natural that this should be the first target for commercial exploration in East Greenland, especially as high quality Upper Permian marine oil source rocks had been identified in the area. Initial hydrocarbon-related investigations were carried out by GGU in the early 1980s, and in 1984 a small group of companies led by Atlantic Richfield Company (ARCO) and later joined by AGIP was awarded an exclusive licence covering the entire Jameson Land Basin. In the following years extensive field studies were carried out by ARCO, often in co-operation with GGU, and 1798 km of reflection seismic data (vibroseis and dynamite) were acquired in the area (Fig. 4). However, in 1990 the consortium decided to relinquish its licence without proceeding to a drilling phase.

As in West Greenland, a reappraisal of relinquished acreage must take into account both the circumstances that can have influenced licensees' decisions and subsequent developments in the area. In the case of Jameson Land it is important to note that the concession was granted just before a dramatic fall in oil prices. Secondly, ARCO's exploration was concentrated on one play type, the Upper Permian carbonate build-up/basinal marine source rock play. *Later work by GGU has shown that there are at least two other plays that should be considered in this basin*: 1) the Upper Carboniferous tilted fault block play, and 2) the Lower Jurassic lacustrine delta play (see later). Interested companies should also be aware that future exploration in the Jameson Land basin can take advantage of the landing strip and supply base established by ARCO at Constable Pynt on the east side of the basin; these facilities are now maintained by the Greenland Home Rule Authorities. Another legacy of ARCO's activities is the large body of open file exploration data, including released seismic data, that is stored in the archives of the Geolgical Survey of Denmark and Greenland.

The KANUMAS project 1990–96

The KANUMAS project was a seismic reconnaissance project in the extreme frontier areas offshore North-East and northern West Greenland (Melville Bay area). The project was initiated by GGU and financed by six major oil companies – BP, Exxon, Japan National Oil Company, Shell, Statoil and Texaco, with a seventh company, Nunaoil A/S, as operator. The project was carried out under the terms of a non-exclusive prospecting licence which gives the partners the opportunity to bid in closed rounds before the first open licensing rounds are held in the survey areas. Seismic acquisition took place in 1991–92 and 1994–95. The seismic vessel used throughout was the Danish Navy high ice-class fisheries inspection vessel *Thetis* which has been adapted to carry seismic equipment. Ice reconnaissance was carried out by a ship-borne helicopter and a naval Gulfstream aircraft equipped with sideward-looking airborne radar (SLAR). In all 4071 km were acquired offshore northern West Greenland, 5637 km off North-East Greenland and 1323 km off central East Greenland (Fig. 2). The results are very encouraging and are summarised in later sections.

The West Greenland revival – 1990 to the present day

In 1989 it was decided that a concerted effort should be made to revive industry interest in West Greenland, since it was evident from a pilot reinterpretation of some of the 1970s seismic data that petroleum exploration in the region had been abandoned prematurely.

Offshore, in addition to further reinterpretation and also reprocessing of older seismic data, a new programme of seismic data acquisition was initiated by GGU, funding being provided by the Mineral Resources Administration for Greenland (MRA). In 1990–92 a total of 8553 km of new data was acquired (Fig. 2), of which 1915 km were acquired as a speculative data by the 1990 contractor, Halliburton Geophysical Services Inc.; Halliburton's data have been taken over by Western Geophysical. A licensing round was held in 1992 for the offshore area between 62°N and 66°N, but no applications were received. In 1994 the Danish-Greenland authorities adopted an open-door policy for offshore southern and central West Greenland. In assessing the reasons for the disappointing response to the 1992 licensing round it is important to realise that the seismic data acquired in 1992 were not available at the time this round was held, because it was in seismic data acquired in this year that *not only very large tilted fault blocks, much larger that any seen in earlier data, but also direct hydrocarbon indicators in the form of flat-spots were discovered.* The area covering these large structures and flat-spots includes Fyllas Banke, and hence is referred to as the Fylla Area.

The results of GGU's 1992 survey were so encouraging that Nunaoil A/S decided to acquire further seismic data in the area on a speculative basis, and in 1994 1706 km new data were acquired on a 10 × 15 km grid. The Nunaoil survey confirmed the existence of flat-spots in the Fylla Area, and company reaction to the new data was very positive. In the light of this encouraging response the Danish-Greenland authorities decided that while applications for areas within the Fylla Area would be considered basically within the framework of the open-door policy previously approved, applications submitted prior to 29 February 1996 would be considered in one process, so that no applications would be negotiated before this date.

At the expiry of the deadline applications for licences in the Fylla Area had been received from two groups of companies, and on 5 December 1996 a licence covering 9427 km^2 was awarded to a consortium of four companies: Den norske stats oljeselskap a.s. (Statoil, operator), Phillips Petroleum International Corporation Denmark, Dansk Olie- og Gasproduktion A/S (DOPAS) and Nunaoil A/S (carried partner in the exploration phase).

Onshore GGU started a new series of studies on the Cretaceous–Tertiary sediments and Early Tertiary volcanic rocks in the Disko–Nuussuaq–Svartenhuk area in 1991, concentrating mainly on Nuussuaq peninsula. The purpose of the new work was to integrate sedimentological, palynological and organic geochemical studies into a new sequence stratigraphic interpretation of the succession. This, it was hoped, would lead to a better insight into the processes controlling deposition of source and reservoir rocks in the area. Ironically, however, it was in the volcanic rocks and not in the sediments that the exploration break-through was made. In 1992 a basalt petrologist found bitumen in vugs and vesicles in basalt outcrops near the base of the Paleocene lava pile. In the following year GGU drilled a slim core well (Marraat-1; Fig. 5) near the site of the original discovery, and *in the uppermost 86 m of the core virtually all porosity in the vesicular parts of the lavas flows was filled by liquid oil and bitumen*. Furthermore, liquid oil and bitumen have since been found in surface outcrops over an area of at least 100 km^2.

Not long after these results had been reported in *GHEXIS Newsletter*, formerly GGU's biannual newsletter to the oil industry, the MRA was approached by the small Canadian company grønArctic Energy Inc. with a view to obtaining a licence in the area. In 1994, under the terms of a prospecting licence, grønArctic drilled a new slim core hole not far from the site of GGU's well, and found further traces of bitumen in the core. In May 1995 grønArctic was awarded an exclusive licence over an area of 1692 km^2 (reduced later to 988 km^2) in the western part of Nuussuaq, and later in the year the company drilled three slim core holes to depths of 901 m, 707 m and 399 m respectively. Gas under pressure was encountered in all three wells, and in the GANE#1 well (see Table 2) liquid oil bled from several levels in the core. Encouraged by these results, grønArctic decided to proceed with drilling conventional deep wells on Nuussuaq in 1996; the first of these, which was completed in September of this year, reached a depth of 2996 m. No details from this well have yet been released.

Table 2. *Summary of wells drilled on Nuussuaq by grønArctic Energy Inc., 1995–1996*

Well	Location	Well depth	Formations drilled	Hydrocarbon showings
GANT#1	70°42.74´N, 53°36.62´W	901 m	Lower Tertiary (?) and Upper Cretaceous clastic sediments	Some gas under pressure in many sandstone units
GANE#1	70°28.25´N, 54°00.40´W	707 m	Lower Tertiary volcanics (0–500 m), Lower Tertiary clastic sediments (500 m–TD)	Oil bleeding from parts of the volcanics; traces of oil and gas under pressure in the sediments
GANK#1	70°28.25´N, 53°51.69´W	399 m	Lower Tertiary volcanics (0–115 m), Lower Tertiary clastic sediments (115 m–TD)	Traces of oil in volcanics; some gas under pressure in sandstones
GRO#3	70°27.77´N 54°05.23´W	2996 m	Lower Tertiary volcanics (0–312 m), sandstones and shales of presumably Early Tertiary and Cretaceous age (312 m–TD)	A number of sandstone intervals contain hydrocarbons.

In 1994 the Danish State and Greenland Home Rule agreed that efforts to stimulate petroleum and mineral exploration in Greenland should be increased, and funds from both parties were pooled and allocated to a number of relevant projects. Amongst these were the drilling of a stratigraphic well on Svartenhuk Halvø ("Halvø" = peninsula), and acquisition of more seismic data in selected areas off West Greenland. The drilling of the stratigraphic well was carried out on the east side of Svartenhuk Halvø in 1995 (Umiivik-1; Fig. 5), with GEUS as operator and grønArctic as contractor. The well was a slim core well which reached the agreed turnkey depth of 1200 m. The well penetrated Upper Cretaceous marine mudstones intruded in the lower part by sills. At the time of writing work on the core has not been completed. However, gas that frothed from the core at several intervals between 900 m and 1175 m is a wet gas with significant amounts of components up to C5.

The 1995 seismic survey consisted of two parts: a 2670 km survey in the fjords and bays around Disko island and Nuussuaq and on the shelf west of Disko, and a 1075 km survey of the area around the Kangâmiut-1 well, including a few supplementary lines near the Ikermiut-1 well and north-west of the Fylla Area (Fig. 2).

Future possibilities

It is expected that petroleum exploration in Greenland will be concentrated in West Greenland for many years to come, although in Jameson Land, where an open-door policy applies today, the Lower Jurassic play may well attract a smaller company that, like grønArctic, is prepared to adopt a less traditional exploration philosophy.

Developments offshore West Greenland will depend very much on the results of exploration in the Fylla Area. There is no doubt that an oil discovery in this area would lead to an immediate revival in interest in other parts of the central and southern West Greenland shelf, in particular the area around the Kangâmiut-1 well and west of the Ikermiut-1 well. Farther north, in Melville Bay, the KANUMAS data have revealed very thick sedimentary successions and large potential trap structures. Were it not for the severe ice conditions in Melville Bay, companies would probably nominate this area as one of the first to be opened for licensing after the Fylla Area. As it is, the Danish-Greenland authorities are taking up a abeyant position as regards Melville Bay.

In the long run the most prospective area in Greenland may be the North-East Greenland shelf, an area which was contiguous with the oil-producing areas of the northern North Sea and West Norwegian shelf prior to the opening of the North Atlantic (see later). However, physical conditions in this area are very severe, with drifting multi-year pack ice all year round. No commercial exploitation of hydrocarbons in this area is forseen before the technical problems of production in such an area have been solved and real oil prices have risen considerably from present-day levels.

Summary of potential petroleum basins in Greenland

Offshore sedimentary basins

Reflection seismic surveys have shown that large sedimentary basins occur offshore East Greenland between 67°–72°N and 75°–77°N, and offshore West Greenland between 63°–68°N and 73°–77°N (Fig. 1). In the intervening areas off both East and West Greenland there are extensive Lower Tertiary basalts below which there are expected to be thick sedimentary successions, but these can only partially be resolved in the seismic data.

North-East Greenland shelf (72°–80°N)

The existence of thick sedimentary sequences in this shelf was first suggested on the basis of interpretation of aeromagnetic data. Judging from the known geology of the Barents Sea, the Norwegian shelf and onshore North-East Greenland, the age of these sediments is likely to be Devonian to Recent, with unconformities in the middle Permian and in the Cretaceous. From the gravity data combined with the structural style seen in some of the seismic lines acquired during the KANUMAS project, the presence of a widespread salt formation has been interpreted on this shelf. By analogy with the geology of the Barents Sea area, it is supposed that this salt is of Late Carboniferous–Early Permian age.

In the shelf between 72°15′–75°30′N extensive volcanic rocks of presumably Early Tertiary age have been interpreted from the aeromagnetic and seismic data. In the near-shore area these are exposed at sea-bed; eastwards they become increasingly deeply buried under younger sediments. It is considered almost certain that the pre-Tertiary sediments interpreted to the north and south of this area continue under the volcanic rocks.

Strong magnetic anomalies suggest the presence of igneous intrusions in the sedimentary and volcanic rocks at around 72°N.

Extensive areas of the North-East Greenland shelf are believed to have considerable petroleum potential. This belief is based on extrapolation from the adjacent onshore area (see later), where oil source rocks and reservoir lithologies are present at several levels, and also from the northern North Sea, West Norwegian shelf and south-west Barents Sea, areas which were contiguous with the North-East Greenland shelf prior to the opening of the Greenland-Norwegian Sea.

East Greenland 70°–72°N (Liverpool Land Basin)

A very thick succession of sediments can be recognised in the seismic data from this area. The sediments are particularly thick within the part of the area underlain by continental crust, where the base of the sediments cannot be identified on the existing data. The upper part of the sedimentary succession is an up to 6 km thick, virtually complete Tertiary succession which forms a large prograding wedge that spread out across both continental and oceanic crust from the mouth of present-day Scoresby Sund. In the part of the area underlain by continental crust the Tertiary succession lies with angular unconformity on block-faulted and tilted sediments of pre-Tertiary (Late Palaeozoic–Mesozoic) age, while where the Tertiary sediments have prograded into the area underlain by oceanic crust, the subsurface consists of subaerial lavas seen as seaward-dipping reflectors in the seismic data.

The Liverpool Land Basin is considered to have a moderate petroleum potential. While the pre-Tertiary succession almost certainly contains sediments of similar age and character as the oil source rocks and reservoir rocks in the onshore basins of East Greenland, these are very deeply buried in the Liverpool Land Basin, and oil source rocks are most likely overmature. Nothing can be deduced about the nature of mudstones in the Tertiary succession, there being no wells in the area. Structures in the Tertiary section are weak, and the best traps are likely to be stratigraphic.

East Greenland 67°–70°N (Blosseville Kyst Basin)

More than 4 km of post-middle Eocene sediments occupy an elongate, coast-parallel sedimentary basin off Blosseville Kyst. The sediments lie entirely on a subsurface of Lower Tertiary basalts. In the area underlain by continental crust there are almost certainly Mesozoic and Paleocene sediments underneath the basalts, as there are onshore and also in ODP well 917A farther to the south. However, it is not possible to interpret the geology underlying the basalts on existing seismic data.

Only the post-basalt Tertiary sediments in the Blosseville Kyst Basin are considered likely to have any potential for petroleum, since any sediments underlying the basalts will be overmature. The outer sediments overlie oceanic crust. Trap structures occur where the sediments drape buried volcanic edifices, and there are also likely to be stratigraphic traps. Submarine fan sandstones fed from the land area to the north are likely to be the best potential reservoirs in the area. Source rocks are most likely to occur in the Eocene–lower Oligocene sediments which were deposited at a time when the area had only limited connections with the early Atlantic Ocean, a factor that would favour oxygen-deficient conditions.

Southern West Greenland (60°–68°N)

As described in the first part of this account, this is the only offshore area in Greenland where the seismic data coverage is better than reconnaissance standard and where exploration wells have been drilled, hence it is the only offshore area where the structural pattern is reasonably well known (Fig. 3, a–c) and where there is some evidence concerning the age and character of the sedimentary basin fill and the timing of at least the younger events in the area.

Offshore southern West Greenland a number of rift basins developed in the Mesozoic which were covered by agrading and prograding sequences during the Tertiary and Quaternary. The earliest sediments offshore southern West Greenland are pre- and syn-rift sequences up to more that 3 km thick; these were not penetrated in any of the wells, but by analogy with the better known Labrador Shelf, they are believed to be Early Cretaceous (Barremian–Albian) in age. These sequences are overlain by a widespread Upper Cretaceous (Cenomanian/Turonian–Maastrichtian) mudstone sequence, the upper part of which was penetrated in the Ikermiut-1 well. Renewed rifting took place at around the Cretaceous-Tertiary boundary, during and after which fan sands intercalated with mudstones were deposited.

Deposition of mudstones continued into the early Eocene, but from middle Eocene sedimentation has been dominated by coarser clastics deposited in simple prograding sequences, with a marked regional unconformity in the middle Eocene. During the Paleocene–Eocene, compressional structures developed in the area west of the Kangâmiut-1 and Ikermiut-1 wells (Fig. 3a) as a consequence of transpression along the transform system linking the sea-floor spreading axis in the Labrador Sea with that in Baffin Bay.

Although results of the first phase of petroleum exploration offshore southern West Greenland were disappointing, the area is believed to have considerable petroleum potential. As mentioned in the first section, four of the five wells drilled did not penetrate structures that could ever have trapped hydrocarbons, and the fifth, the Kangâmiut-1 well, did encounter hydrocarbons but was not properly tested. In the offshore southern West Greenland basins oil source rocks are now interpreted as most likely to occur at the base of a widespread Upper Cretaceous (Cenomanian/Turonian–Campanian) mudstone, a level not penetrated by any of the wells. Another possible source rock level is in the Paleocene, since uppermost Maastrichtian–lower Paleocene source rocks are believed to the source of many of the live oil showings on the Nuussuaq peninsula farther north (see section on onshore basins). Reservoir is most likely to be provided by syn-rift Lower Cretaceous sandstones and by both fan and deltaic Paleocene sandstones. The main play type involves block-faulted and tilted Lower Cretaceous sandstone reservoirs sourced by Cenomanian/Turonian mudstones and sealed by the Cenomanian/Turonian mudstones and Paleocene mudstones which drape the fault blocks. Direct hydrocarbon indicators in the form of flat-spots have been observed in this type of structure in seismic data acquired in the Fylla Area south-west of Nuuk/Godthåb. If these flat-spots represent gas-liquid contacts, very large reserves of gas are present in this area, possibly underlain by an oil column. Other play types are: i) anticlinal compressional structures west of the Ikermiut-1 well, with Cenomanian/Turonian source rocks sourcing and sealing Lower Cretaceous sandstone reservoirs; ii) the Kangâmiut play, where Campanian–Paleocene sandstone wedges shed off a gneiss ridge could be sourced and sealed by Paleocene mudstones; older mudstones could also source these sandstone reservoirs; iii) a major Upper Cretaceous prograding structure east of the Kangâmiut-1 well which could provide stratigraphic traps for hydrocarbons sourced from a Cenomanian/Turonian source rock.

Central West Greenland (68°–73°N)

The Lower Tertiary basalts exposed onshore in the Disko–Nuussuaq–Svartenhuk Halvø area continue offshore where they have been mapped from seismic and magnetic data over the entire area between 68° and 73°N. In the eastern part of this area the basalts are exposed at sea-bed and have been sampled by dredging, but to the west they become increasingly buried under a cover of Eocene and younger sediments. While the upper surface of the basalts can be mapped easily from the seismic data, the base of the basalts usually cannot be interpreted and there are seldom distinct reflections from the underlying formations. Locally, however, as for example at *c.* 69°30´N, the basalts are thinner, and reflections from underlying sediments can be seen. In this area the basalts are only about 1300 m thick, and the thickness of underlying sediments may be as much as 5 km.

Until recently offshore central West Greenland was regarded as unprospective for hydrocarbons, but the discovery of live oil on Nuussuaq peninsula in the adjoining onshore area has lead to a much more positive assessment of the offshore area. In the first place there are both tilted fault blocks and inversion anticlines that affect the basalts and underlying sediments (Fig. 3d), and to some extent also the lower Eocene; some of these structures could provide structural traps. Secondly, the oil discovered on Nuussuaq is so widespread and includes so many types of oil (see section on onshore basins) that more than one effective source rock must occur below the basalts. This could source both subbasaltic plays and, if the oil has leaked through the basalts, reservoirs in the overlying Eocene. There is also the possibility that source rocks were deposited in restricted basins above the basalts.

Northern West Greenland (73°–78°N)

North of 73°N the new seismic data acquired as part of the KANUMAS project have confirmed the existence of very deep graben/half-graben west and south-west of Melville Bay (Fig. 3e). This basin had already been outlined from aeromagnetic and gravity data acquired in the late 1960s and early 1970s. The new data have also revealed several other graben and half-graben structures all the way to the northern limit of the survey at 76°30′N. In the Melville Bay graben the thickness of sediments exceeds 13 km. In the absence of wells, interpretations of the age of the sediments and timing of structural events in the area are almost entirely based on analogy with the onshore geology of West Greenland and north-east Canada.

According to current interpretations, rifting took place in two main phases: Early Cretaceous and Late Cretaceous (Senonian)–Paleocene. During these phases great thicknesses of syn-rift sediments were deposited in the developing graben and half-graben. The intervening Cenomanian–Turonian interval is thought to have been one of thermal subsidence during which mudstones were deposited. In early Eocene time inversion took place in the northern part of the area, and large anticlines were formed (Fig. 3e). Eocene–Recent sedimentation has been largely by progradation into a subsiding basin.

Although exploration offshore northern West Greenland is not yet beyond the reconnaissance stage, there are grounds for believing that the area has a large petroleum potential. Very large potential trap structures, both draped tilted fault blocks and anticlines generated during inversion, have been identified on the seismic sections. Oil source rocks are thought to be likely to occur in the Cenomanian–Turonian mudstones interpreted from the seismic data and in the uppermost Maastrichtian–Paleocene section. Support for these suggestions has recently come from the discovery of mudstones with oil source rock characteristics near the base of a regional transgressive late Cenomanian–Maastrichtian mudstone formation (Kanguk Formation) in the Canadian Arctic Islands and the discovery of live oil occurrences on the Nuussuaq peninsula farther south (see later). Sandstones with reservoir properties can be expected to occur at several levels in the syn-rift successions.

Onshore basins

Franklinian Basin, North Greenland (80°–83°N)

This is the eastern continuation of the Franklinian Basin of arctic Canada. The basin developed along the northern margin of the Laurentian craton during earliest Cambrian to Late Silurian time, extending into the Devonian in Canada. Until the end of the Early Silurian (late Llandovery) there were two main facies belts – a stable platform along the southern margin of the basin on which initial deposition of shallow-water sandstones and mudstones was succeeded by a long period of carbonate deposition, and a deep water trough to the north in which substantial thicknesses of siliciclastic sediments were deposited. In latest Llandovery time the entire marginal carbonate shelf collapsed and both shelf and trough were inundated by thick turbidites derived from the east. Good Type II oil source rocks are found in both Lower–Middle Cambrian and Lower Silurian outer shelf terrigenous and carbonate mudstones. Potential reservoirs include Lower and Middle Cambrian shelf sandstones and Lower Silurian reef and platform margin carbonate build-ups. The most promising play involves long-distance migration up-dip from Middle Cambrian source rocks into Lower Cambrian shelf sandstones.

Late Palaeozoic–Mesozoic rift basins of North-East Greenland (72°–76°N)

Rifting in East Greenland began in the Middle Devonian when parts of the Caledonian orogen collapsed and a major molasse basin developed. Rifting continued until the Late Carboniferous, and substantial thicknesses of non-marine clastic sediments accumulated in the resulting grabens and half-grabens. After a period of erosion, sedimentation resumed in the middle Permian under generally more tranquil conditions and continued intermittently until the Late Jurassic. Apart from carbonates and evaporites deposited in the Late Permian, sediments deposited during the Late Permian–Late Jurassic were almost entirely shallow marine and non-marine sandstone and mudstones. In earliest Cretaceous time rifting was renewed, and in the northern part of the area very thick wedges of coarse clastic sediments were deposited in subsiding half-grabens. Fault movements continued along the western margin of the area during the Cretaceous, but away from the influence of these faults only mudstones and fine-grained sandstones were deposited.

There are several intervals with oil source rocks in the Upper Palaeozoic and Mesozoic of this area; the most important source rocks are: i) Upper Carboniferous Type I–II lacustrine mudstones with very high generative potential but restricted lateral extent. ii) Upper Permian Type II marine mudstones with wide aerial extent and high generative potential. iii) Upper Jurassic mudstones which are gas-prone in onshore outcrops but are likely to be oil-prone on the continental shelf to the east. There are also several potential reservoir units, in particular Upper Carboniferous fluvial sandstones, Upper Permian carbonates, Upper Jurassic sandstones, and uppermost Jurassic-Lower Cretaceous syn-rift conglomerates and sandstones. Tilted faults blocks provide potential structural traps, and there are also stratigraphic plays involving Permian carbonate reservoirs. From regional mapping and maturity considerations an area of about 6000 km^2 is considered to have potential prospectivity, but at present there are no seismic data on which to base a more stringent evaluation of prospectivity.

Jameson Land Basin, East Greenland (70°30´–72°N)

This basin, which extends over an area of about 10 000 km^2 (Fig. 4), is covered by a 1798 km seismic survey carried out by ARCO in 1985–89, and hence is better known than the basins to the north. The structural history of the basin is also different in that while rifting began in the Devonian, virtually no faulting affected the basin after the mid-Permian, Late Permian-Mesozoic deposition in the basin being governed by thermal subsidence. During the latter phase more than 5 km of sediments were deposited.

As in the basins to the north, the Devonian through Lower Permian succession in Jameson Land consists almost entirely of conglomerates, sandstones and mudstones of fluviatile and lacustrine origin. In the Late Permian a marine transgression inundated the area. In shallow water areas carbonates were deposited; both reef and platform facies associations were developed. In basinal areas organic-rich mudstones were laid down. Following an interval of regional lowering of relative sea level and subaerial exposure, the carbonate reefs once again became submerged, and as relative sea level rose they became drowned and covered by dark mudstones.

In Early Triassic time continental conditions returned, and sedimentation took place in an arid inland basin. Alluvial fan conglomerates and sandstones around the periphery give way to finer-grained fluviatile sediments in the centre of the basin. At the end of the Triassic a large anoxic lake formed in the centre of the area; this became connected to the sea during an Early Jurassic marine transgression, while alluvial flood plain and deltaic sedimentation persisted around the margins of this newly established shallow marine basin. For the remainder of the Jurassic and into Early Cretaceous marine sedimentation continued, with deposition of sands and muds being controlled by variations in sediment input and sea level. The youngest sediments onshore are of earliest Cretaceous age, but younger Cretaceous sediments are likely to occur under Scoresby Sund to the south.

The most important source rocks in the Jameson Land Basin are Upper Carboniferous lacustrine mudstones (Type I), Upper Permian basinal marine mudstones (Type II), and lowermost Jurassic lacustrine mudstones (Type I–II). Potential reservoirs are Upper Carboniferous (and possibly older) fluvial sandstones, Upper Permian carbonates, and Lower Jurassic deltaic sandstones. The main play types are i) mudstone-draped tilted Carboniferous fault blocks, with lacustrine mudstones as source and fluviatile sandstones as reservoir, ii) Upper Permian carbonate build-ups sourced and sealed by Upper Permian marine mudstones (this was the main target for ARCO exploration), and iii) lowermost Jurassic lacustrine deltaic sandstones interfingering with lacustrine mudstones which act as both source and seal; this play is either purely stratigraphic or structural where the sediments have been folded in gentle roll-over anticlines associated with small-offset normal faults. Main risk factor in the Jameson Land Basin is a Tertiary uplift of 2 km or more.

Nuussuaq Basin, central West Greenland (69°–72°N)

Cretaceous–Tertiary sediments overlain by volcanic rocks outcrop in the Disko–Svartenhuk region of West Greenland (Fig. 5). These sediments were laid down in a basin, the Nuussuaq Basin, which is bounded to the east by an extensional fault system. Recently acquired seismic data indicate that the maximum thickness of sediments in the basin exceeds 8 km, but the age and character of the deepest sediments are not known.

The exposed Cretaceous sediments, which are of Albian to late Campanian or early Maastrichtian age, were deposited in a fluvial- and wave dominated delta environment. Pre- and syn-rift fluvial sandstones with minor mudstone and coal characterise the south and east of the outcrop area. To the north-west these give way to stacked, typical deltaic, coarsening-upwards successions, often ending with a coal layer, while farther north-west dark mudstones were deposited in a purely marine environment.

During the Maastrichtian the area became tectonically unstable. Phases of uplift were followed by incision of valleys in the underlying sediments. Conglomerates and both turbiditic and fluvial sands and mudstones of late Maastrichtian to middle Paleocene age filled the valleys, while on the slope to the west more than 2.5 km of turbidite sandstones alternating with marine mudstones were deposited.

The recent discovery of live oil in Nuussuaq both in outcrops of vesicular basalt over an area of at least 100 km^2 and in vesicular zones and fractures in basalts penetrated in three slim core wells proves that the Nuussuaq Basin is a potential petroleum basin. Biomarkers in some of the oil samples are characteristic of Tertiary deltaic oils, so the source for these oils is expected to be in the underlying uppermost Maastrichtian–lower Paleocene sediments. Other surface samples have a more complex origin; no fewer than five types of oil have been identified by the Survey's laboratories. Evidence of a deeper source rock was obtained on the north side of Nuussuaq when wet gas was encountered in fractured Upper Cretaceous mudstones during drilling for hard minerals (Serfat site, Fig. 5), indicating that there is an unexposed Cretaceous source rock in this area. Reservoirs in the Nuussuaq Basin may be either middle–Upper Cretaceous deltaic sandstones or uppermost Maastrichtian–Early Paleocene turbidite sandstones.

Selected references

Bate, K. J., Whittaker, R. C., Chalmers, J. A. & Dahl-Jensen, T. 1995: The Fylla structural complex: possible very large gas reserves offshore southern West Greenland. *Rapport Grønlands Geologiske Undersøgelse* **165**, 22–27.

Chalmers, J. A.: New evidence on the structure of the Labrador Sea/Greenland continental margin. *Journal of the Geological Society, London* **148**, 899–908.

Chalmers, J. A. & Laursen, K. H. 1995: Labrador Sea: the extent of continental and oceanic crust and the timing of the onset of seafloor spreading. *Marine and Petroleum Geology* **12**, 205–217.

Chalmers, J. A. & Pulvertaft, T. C. R. 1993: The southern West Greenland continental shelf – was petroleum exploration abandoned prematurely? *In* Vorren, T. O. *et al.* (edit.) *Arctic geology and petroleum potential*, 55–66. Amsterdam: Elsevier for Norwegian Petroleum Society.

Chalmers, J. A., Pulvertaft, T. C. R., Christiansen, F. G., Larsen, H. C., Laursen, K. H. & Ottesen, T. G. 1993: The southern West Greenland continental margin: rifting history, basin development and petroleum potential. *In* Parker, J. R. (edit.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, 915–931. London: Geological Society.

Chalmers, J. A., Dahl-Jensen, T., Bate, K. J. & Whittaker, R. C. 1995: Geology and petroleum prospectivity of the region offshore southern West Greenland. *Rapport Grønlands Geologiske Undersøgelse* **165**, 13–21.

Christiansen, F. G. (edit.) 1989: Petroleum geology of North Greenland. *Bulletin Grønlands Geologiske Undersøgelse* **158**, 92 pp.

Christiansen, F. G., Dam, G. & Pedersen, A. K. 1994: Discovery of live oil at Marraat, Nuussuaq: field work, drilling and logging. *Rapport Grønlands Geologiske Undersøgelse* **160**, 57–63.

Christiansen, F. G., Bojesen-Koefoed, J., Dam, G., Nytoft, H.-P., Larsen, L. M., Pedersen, A. K. & Pulvertaft, T. C. R. 1996: The Marraat oil discovery on Nuussuaq, West Greenland: evidence for a latest Cretaceous–earliest Tertiary oil prone source rock in the Labrador Sea–Melville Bay region. *Bulletin of Canadian Petroleum Geology* **44**, 39–54.

Christiansen, F. G., Dam, G., Piasecki, S. & Stemmerik, L. 1992: A review of Upper Palaeozoic and Mesozoic source rocks from onshore East Greenland. *In* Spencer, A. M. (edit.) Generation, accumulation and production of Europe's hydrocarbons. *Special Publication of the European Association of Petroleum Geologists* **2**, 151–161.

Dam, G. & Surlyk, F. 1992: Forced regressions in a large wave- and storm-dominated anoxic lake, Rhaetian–Sinemurian Kap Stewart Formation, East Greenland. *Geology* **20**, 749–752.

Dam, G. & Christiansen, F. G. 1990: Organic geochemistry and source rock potential of the lacustrine shales of the Upper Triassic–Lower Jurassic Kap Stewart Formation, East Greenland. *Marine and Petroleum Geology* **7**, 428–443.

Dam, G. & Sønderhom, M. 1994: Lowstand slope channels of the Itilli succession (Maastrichtian–Lower Paleocene), Nuussuaq, West Greenland. *Sedimentary Geology* **94**, 49–71.

Larsen, H. C. 1984: Geology of the East Greenland shelf. *In* Spencer, A. M. (edit.) *Petroleum Geology of the North European margin*, 329–339. London: Graham & Trotman.

Larsen, H. C. 1985: Project NAD – East Greenland. An integrated aeromagnetic and marine geophysical project off the east coast of Greenland. Final report. Internal report, Geological Survey of Greenland.

Larsen, H. C. 1990: The East Greenland shelf. *In* Grantz, A., Johnson, L. & Sweeney, J. F. (edit.) *The Arctic Ocean region. The geology of North America* **L**, 185–210. Boulder, Colorado: Geological Society of America.

Larsen, H. C. & Jakobsdóttir, S. 1988: Distribution, crustal properties and significance of the seawards-dipping sub-basement reflectors off E Greenland. *In* Morton, A. C. & Parson, L. M. (edit.) *Early Tertiary volcanism and the opening of the NE Atlantic. Special Publication of the Geological Society, London* **39**, 95–114.

Larsen, H. C. & Marcussen, C. 1992: Sill-intrusion, flood basalt emplacement and deep crustal structure of the Scoresby Sund region, East Greenland. *In* Storey, B. C., Alabaster, T & Pankhurst, R. J. (edit.) *Magmatism and the causes of continental break-up. Special Publication of the Geological Society, London* **68**, 365–386.

Larsen, H. C., Saunders, A. D., Clift, P. & ODP Leg 152 Party 1994: Initial Report, ODP Leg 152. College Station: Texas A & M University, 977 pp.

Nøhr-Hansen, H. 1996: Dinoflagellate cyst stratigraphy and sequence stratigraphic correlation of Upper Cretaceous to upper Paleogene from three wells, offshore central West Greenland. Program and Abstracts, Ninth International Palynological Congress, Houston, 117 only.

Mathiesen, A., Christiansen, F. G., Bidstrup, T., Marcussen, C., Dam, G., Piasecki, S. & Stemmerik, L. 1995: Modelling of hydrocarbon generation in the Jameson Land basin, East Greenland. *First Break* **13**, 330–341.

Stemmerik, L., Christiansen, F. G., Piasecki, S., Jordt, B., Marcussen, C. & Nøhr-Hansen, H. 1993: Depositional history and petroleum potential of the Carboniferous to Cretaceous sediments in the northern part of East Greenland. *In* Vorren, T. O. *et al.* (edit.) *Arctic geology and petroleum potential*, 67–86. Amsterdam: Elsevier for Norwegian Petroleum Society.

Surlyk, F. 1978: Submarine fan sedimentation along fault scarps on tilted fault blocks (Jurassic–Cretaceous boundary, East Greenland). *Bulletin Grønlands Geologiske Undersøgelse* **128**, 108 pp.

Thorning, L., Larsen, H. C. & Jacobsen, N. L. 1982: Project Eastmar – final report. Internal report, Geological Survey of Greenland, 82 pp.

Whittaker, R. C. 1995: A preliminary assessment of the structure and petroleum potential offshore central West Greenland. *Open File Series Grønlands Geologiske Undersøgelse* **95/9**, 33 pp.

Whittaker, R. C. & Hamann, N. E. 1995: The Melville Bay area, North-West Greenland – the first phase of petroleum exploration. *Rapport Grønlands Geologiske Undersøgelse* **165**, 28–31.

Whittaker, R. C., Hamann, N. E. & Pulvertaft, T. C. R. 1997: A new frontier province offshore northern West Greenland: structure, basin development and petroleum potential of the Melville Bay area. *Bulletin of the American Association of Petroleum Geologists* **81**

Figures

Figure 1. *Map of sedimentary basins in Greenland.*

Figure 2. *Map showing seismic lines acquired offshore Greenland since 1980.*

Figure 3. *Representative cross-sections of West Greenland basins based on interpreted seismic lines; a–c: southern West Greenland; d: central West Greenland c. 69°30´N; e: Melville Bay.*

Figure 4. *Map of the Jameson Land Basin with position of seismic lines.*

Figure 5. *Map of the Disko–Nuussuaq–Svartenhuk area with positions of wells drilled in the period 1993–1996.*

SEDIMENTARY BASINS OF GREENLAND

by the

Geological Survey of Denmark and Greenland

LEGEND

- Inland Ice
- Lower Tertiary basalts
- Cretaceous-Lower Tertiary sediments of West Greenland (Nuussuaq Basin) and East Greenland (Kangerlussuaq Basin)
- Carboniferous-Lower Tertiary sediments of the Wandel Sea Basin of eastern North Greenland
- Carboniferous-Cretaceous sediments of North-East Greenland basins
- Carboniferous-Cretaceous sediments of the Jameson Land Basin in East Greenland
- Devonian Basin of North-East Greenland
- Shelf } Lower Palaeozoic sediments of North Greenland (Franklinian Basin)
- Trough } Lower Palaeozoic sediments of North Greenland (Franklinian Basin)
- Middle-Late Proterozoic sediments and volcanic rocks
- Caledonian orogenic belt
- Early Proterozoic orogenic belts
- Archaean craton
- Intrusive complexes; Early Tertiary in East Greenland, Middle Proterozoic in South Greenland
- Offshore basins with substantial thicknesses of sediments (>~3km)
- Offshore basins where deeper sedimentary successions concealed by Lower Tertiary basalts
- Landward limit of proven oceanic crust
- Extensional fault
- Compressional fault, thrust
- Transform fault
- Site of exploration well

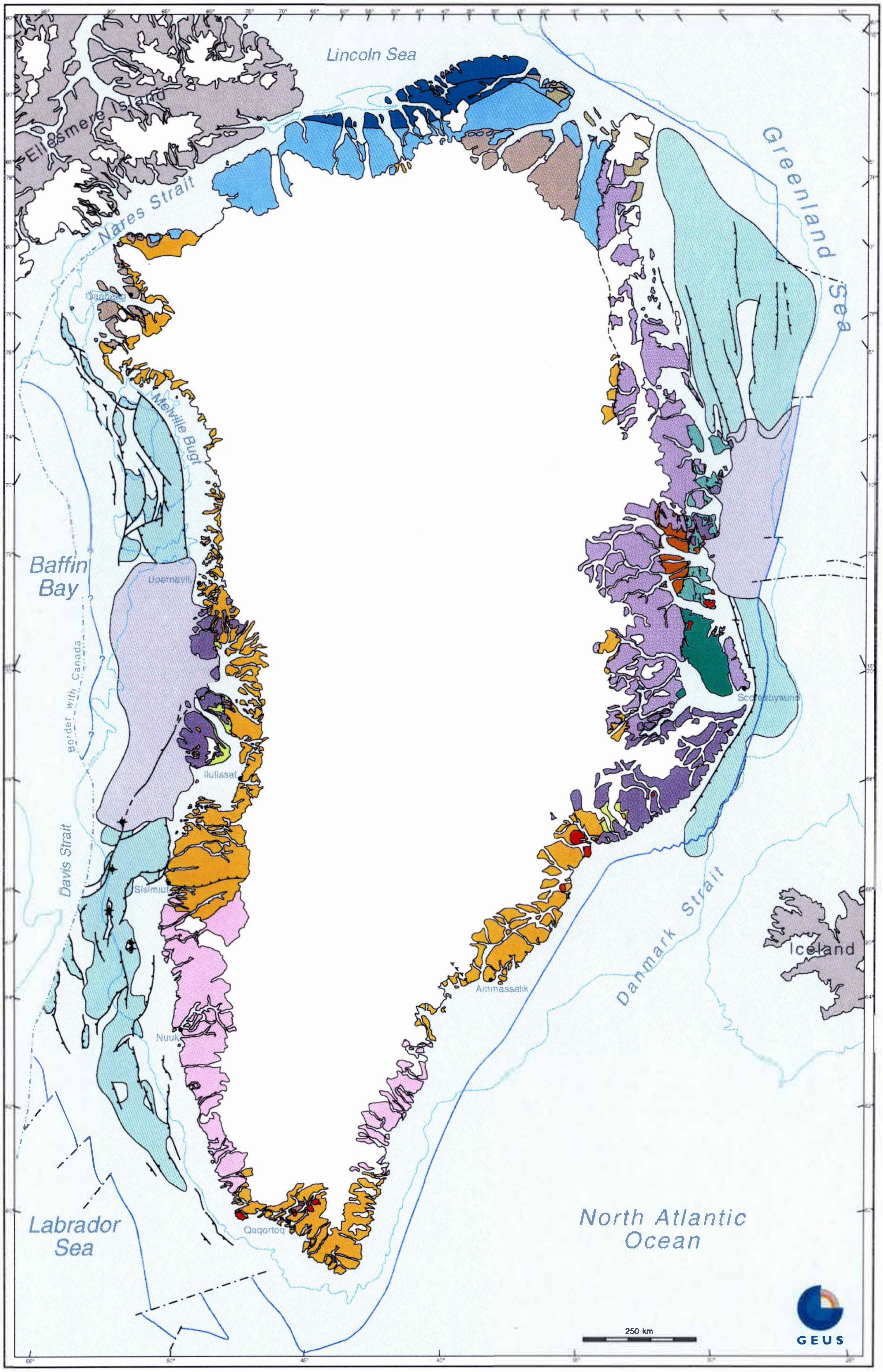

Figure 1. Map of sedimentary basins in Greenland.

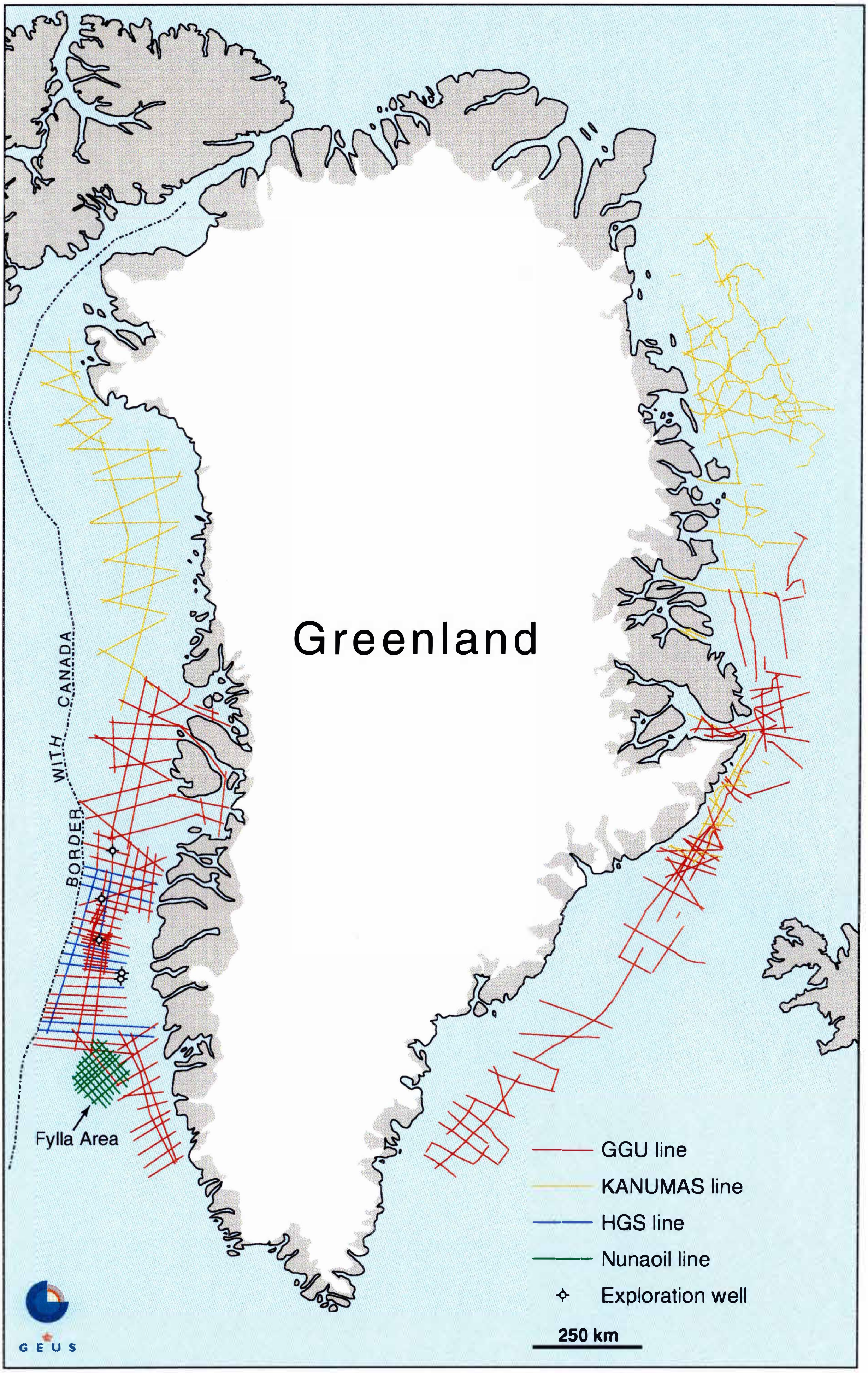

Figure 2. Map showing seismic lines acquired offshore Greenland since 1980.

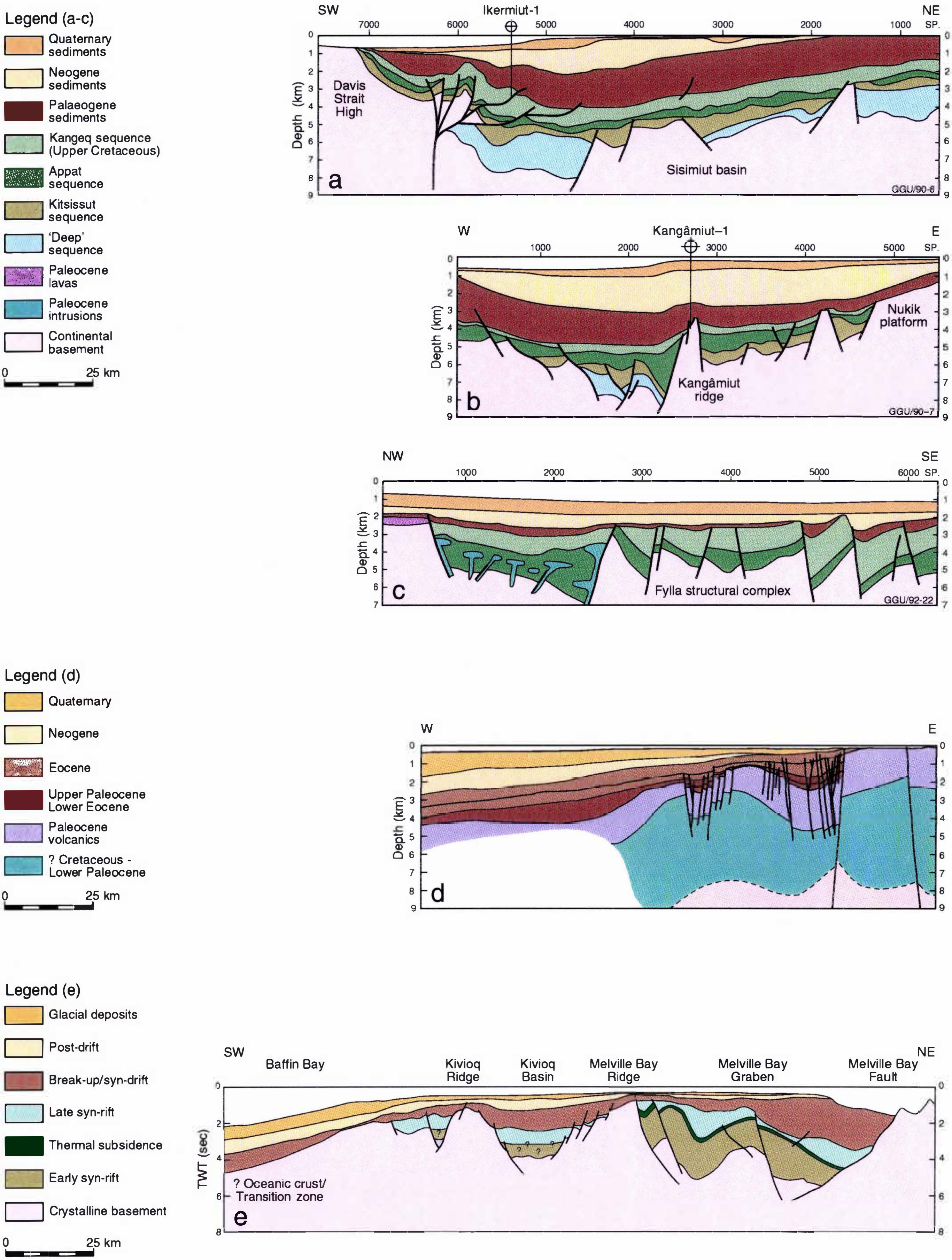

Figure 3. Representative cross-sections of West Greenland basins based on interpreted seismic lines; a-c: southern West Greenland; d: central West Greenland; e: Melville Bay.

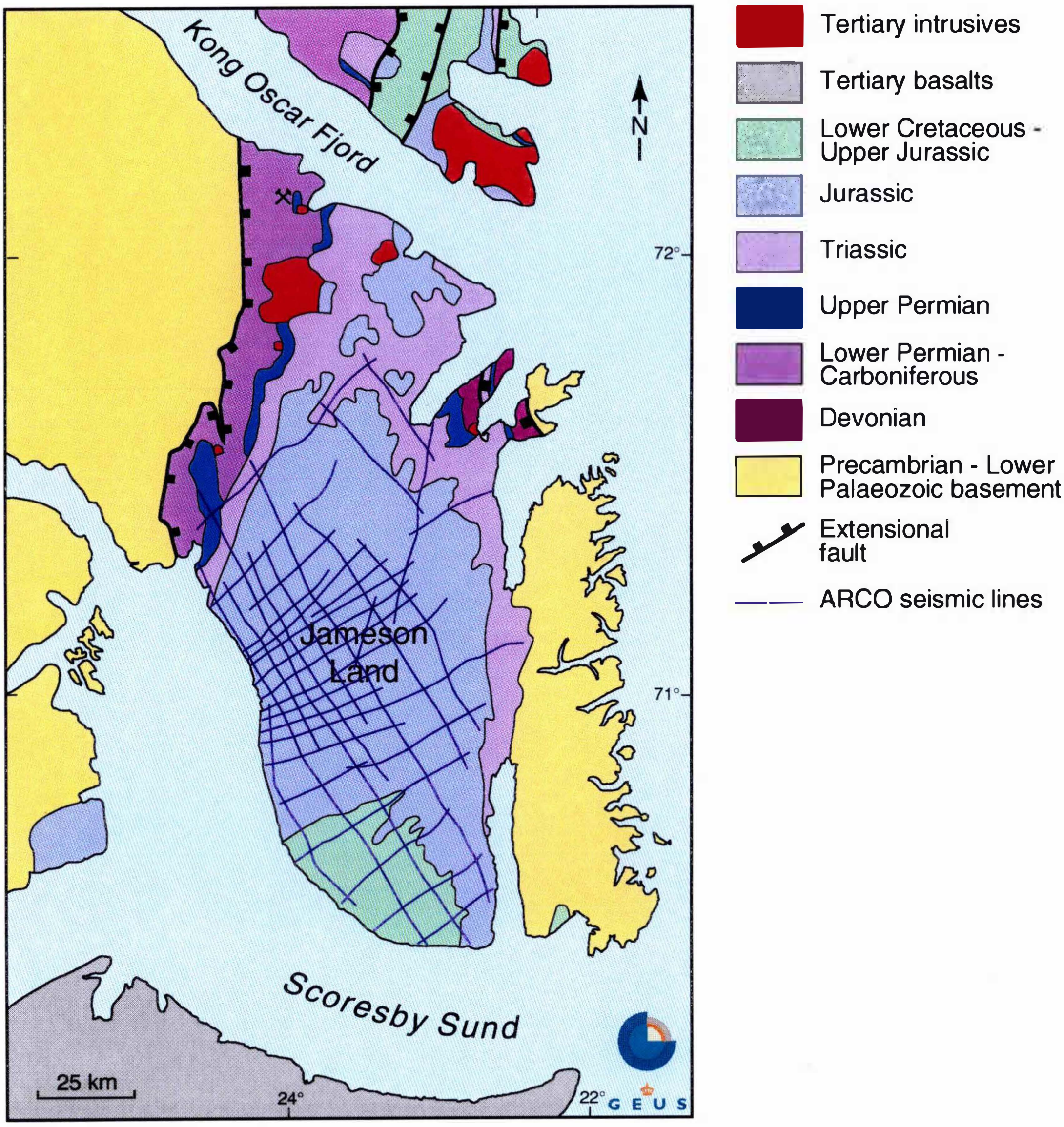

Figure 4. Map of the Jameson Land Basin with position of seismic lines.

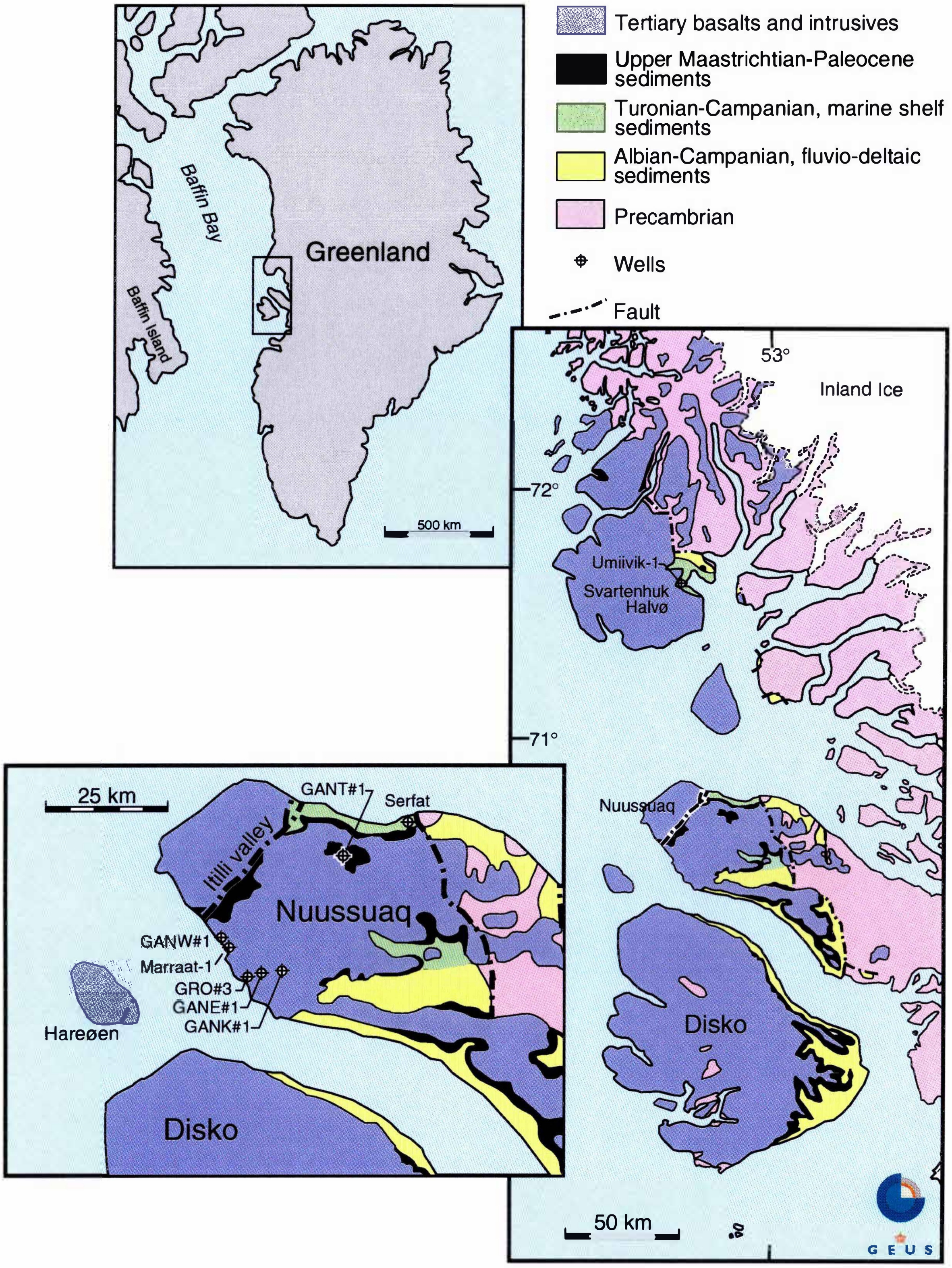

Figure 5. Map of the Disko-Nuussuaq-Svartenhuk area with positions of wells drilled in the period 1993-1996.