Petroleum geological activities in West Greenland in 1998

Flemming G. Christiansen, Anders Boesen, Jørgen A. Bojesen-Koefoed, James A. Chalmers, Finn Dalhoff, Gregers Dam, Birgitte Ferré Hjortkjær, Lars Kristensen, Lotte Melchior Larsen, Christian Marcussen, Anders Mathiesen, Henrik Nøhr-Hansen, Asger K. Pedersen, Gunver K. Pedersen, T. Christopher R. Pulvertaft, Nina Skaarup and *Martin Sønderholm*

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

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

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

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

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

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

Field work in the Disko–Nuussuaq region

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

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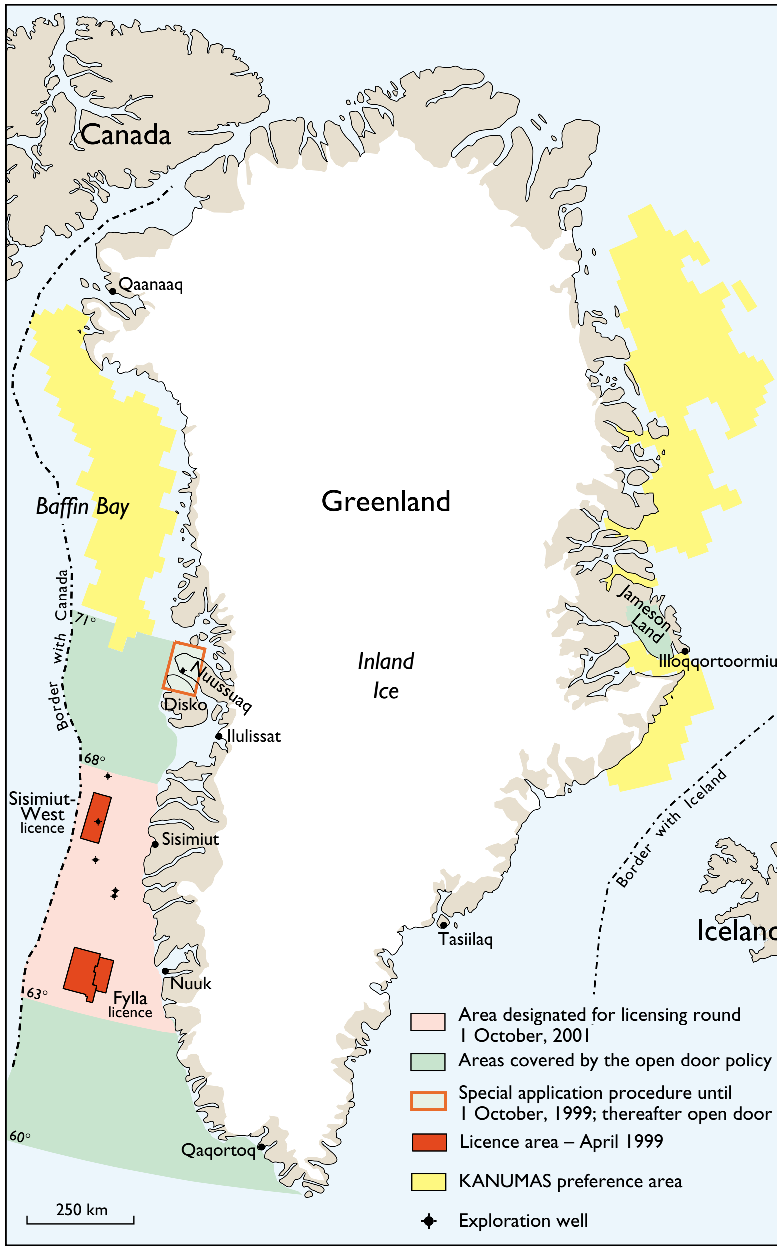
Fig. 1. Map showing areas offshore Greenland to be opened in a new licensing round, areas covered by an open door policy, KANUMAS preference areas, and licence areas. Modified from the Survey's *Ghexis Newsletter* 15, (April 1999).



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

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

Atane Formation

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

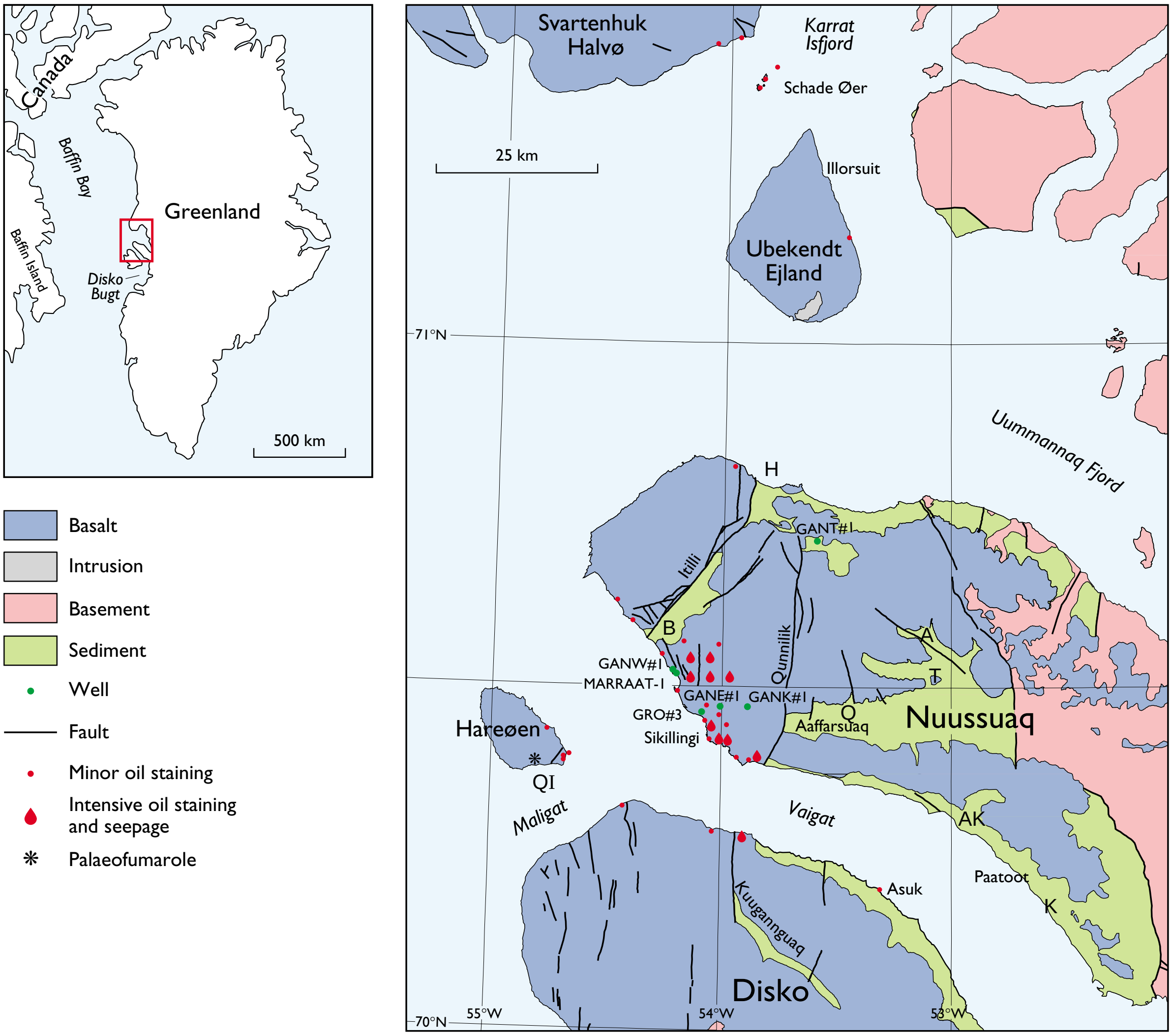


Fig. 2. Simplified geological map of the Disko – Nuussuaq – Svartenhuk Halvø area showing the position of wells and boreholes, and distribution of localities with seepage and staining of oil found in the period 1992–98. **A**: Agatdalen (with Baculiteskløft and Scaphitesnæsen). **AK**: Atlaata Kuua.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

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

Neogene–Quaternary section on Hareøen

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

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

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

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

Evidence for an early Campanian tectonic unconformity

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

Structural studies on Nuussuaq

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

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

Palaeogene volcanic rocks

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

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

Structural compilation of Svartenhuk Halvø

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

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

Release of data from the GRO#3 well

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

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

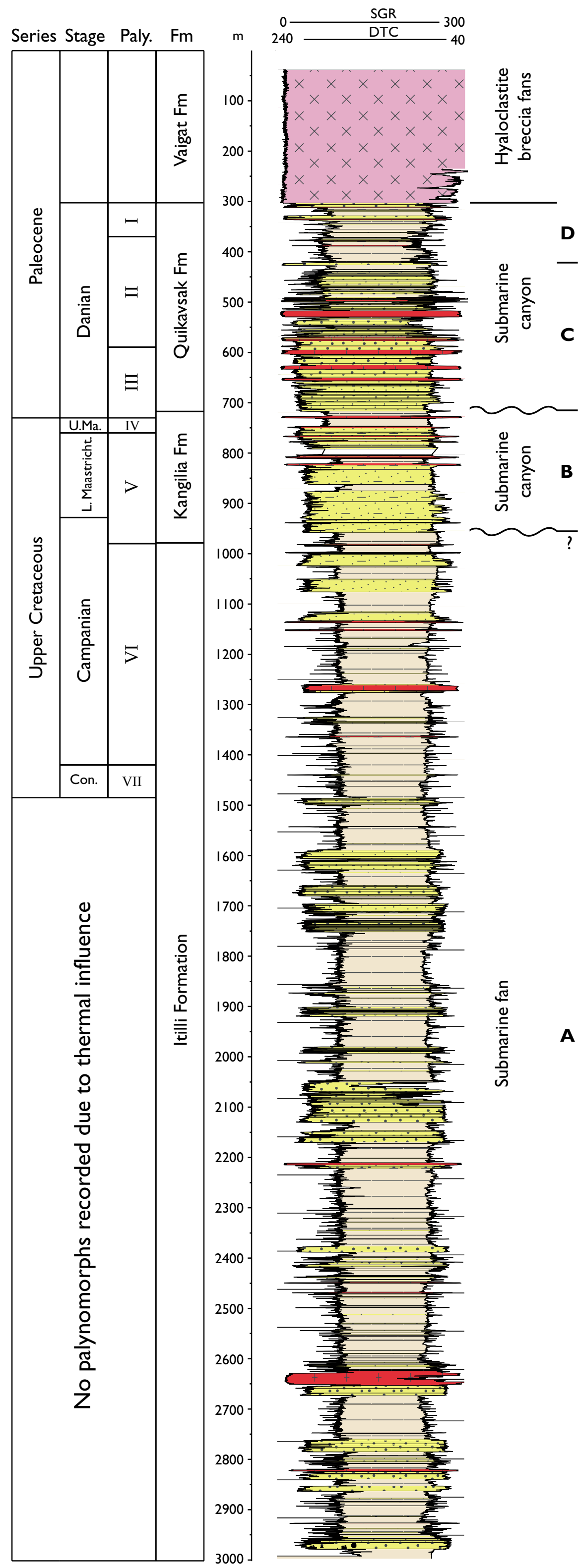
A lithological and petrophysical evaluation of the well has been undertaken by the Survey (Kristensen & Dam 1997), and the organic geochemistry and the biostratigraphy have been described by Bojesen-Koefoed *et al*. (1997) and Nøhr-Hansen (1997), respectively.

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

Stratigraphic units

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

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



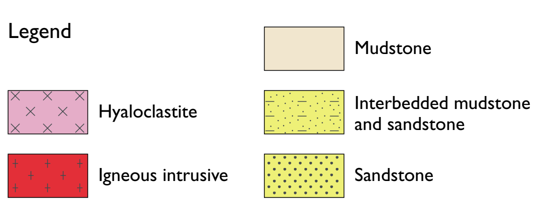


Fig. 5. Log of the GRO#3 well.

and a similar depositional environment is suggested for Unit A.

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

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

Petrophysical evaluation

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

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

Organic geochemistry and thermal maturity

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

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

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

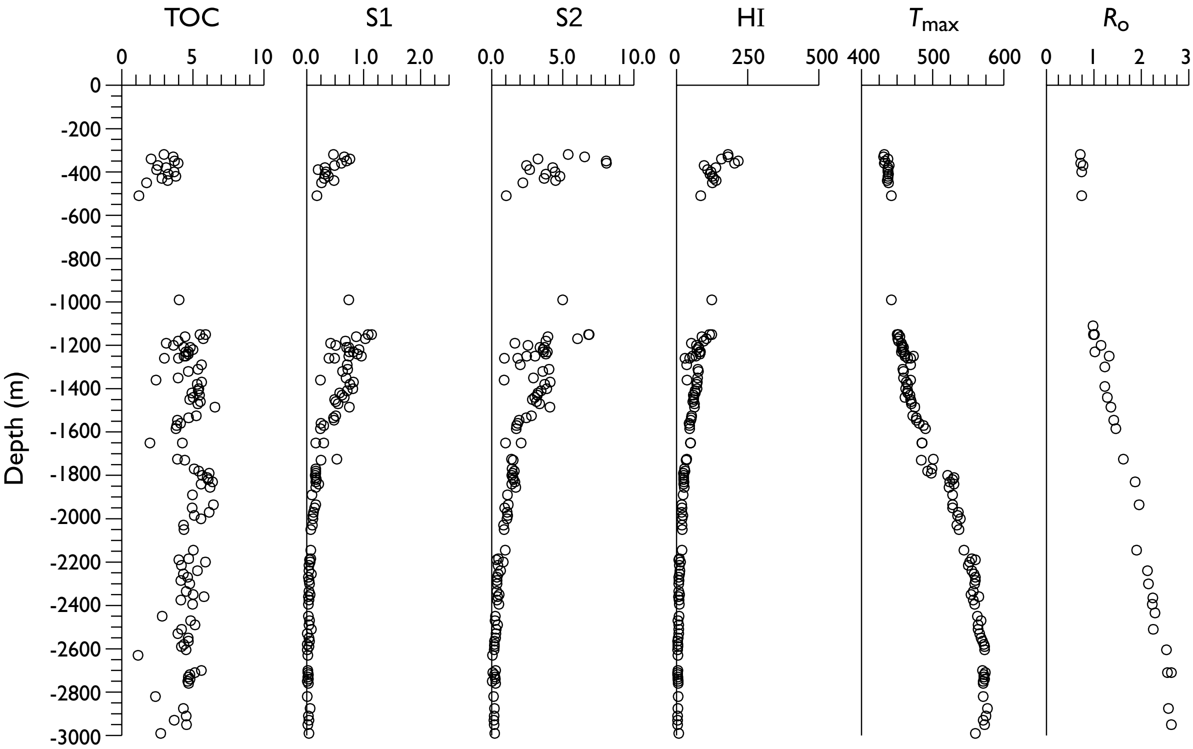


Fig. 6. Organic geochemical and thermal maturity parameters versus depth for the GRO#3 well. **TOC**: Total organic carbon (%). **S1**: Hydrocarbons already present in the rock (mg HC/g rock). **S2**: Hydrocarbons generated during pyrolysis (mg HC/rock). **HI**: Hydrogen index. $\boldsymbol{T_{max}}$: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

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

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

Basin modelling

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

Offshore West Greenland

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

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

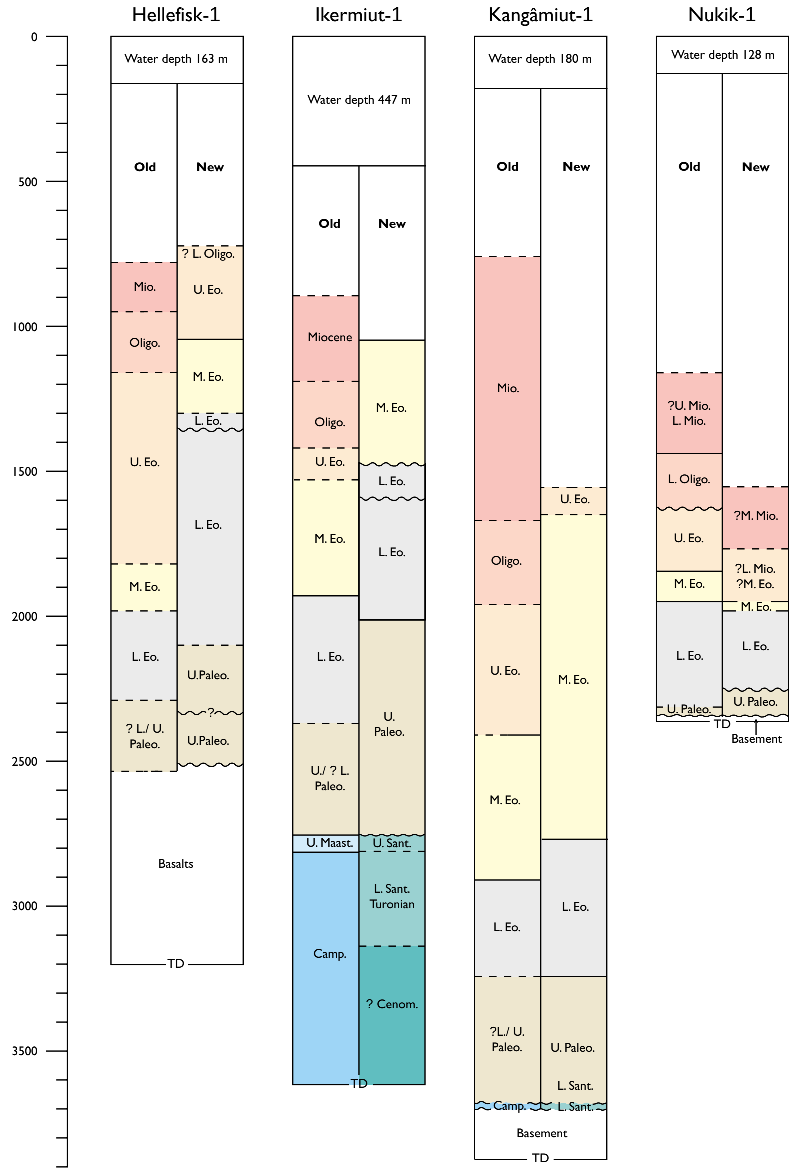


Fig. 7. Summary of the new palynostratigraphy offshore West Greenland based on four wells. Modified from Nøhr-Hansen (1998).

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

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

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

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

Future Survey work in West Greenland

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

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

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

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

Acknowledgements

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

The sedimentological studies by Gregers Dam are financed by the Carlsberg Foundation (grant no. 980037/20-1224). The background work for developing the palynostratigraphy offshore West Greenland was financially supported by the EFP-91 project 'Basin modelling, West Greenland' (EFP 1313/91-0014). The project 'Modelling of uplift history from maturity and fission track data, Nuussuaq, West Greenland' was supported by EFP-95 (EFP 1313/95-0004). The petrophysical study of the GRO#3 well was financially supported by the EFP-96 project 'Reservoir modelling of western Nuussuaq, central West Greenland' (EFP 1313-96-0010).

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Authors' addresses:

F.G.C., A.B., J.A.B.-K., J.A.C., F.D., G.D., B.F.H., L.K., L.M.L., C.M., A.M., H.N.-H., T.C.R.P. & N.S., *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark.* E-mail: *fgc@geus.dk*

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

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

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