DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1998/6

Reservoir characterisation of western Nuussuaq, central West Greenland

Compiled by
Martin Sønderholm and Gregers Dam

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

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Contents

Introduction

The background for the project is a series of petroleum geological activities in the Disko–Nuussuaq–Svartenhuk Halvø region of central West Greenland which started with the discovery of oil in basalts at Marraat on the Nuussuaq peninsula in 1992 (Fig. 1; Christiansen 1993; Christiansen *et al.* 1994). The discovery of oil in the region revised the existing opinion that the whole of the Labrador Sea–West Greenland region was gas-prone. In particular, the presence of oil impregnation in vesicular zones throughout the uppermost 90 m of the Marraat-1 core and a seismic section along the south coast of Nuussuaq indicating a sedimentary section of 6–8 km thick (Christiansen *et al.* 1995) promoted the Nuussuaq Basin from being a study model for the offshore regions to be an exploration target on its own. Shortly after completion of the Survey field work in 1994, a newly established Canadian company (grønArctic Energy Inc. of Calgary) was granted an onshore prospection license on Nuussuaq. After granting of this licence grønArctic drilled the GANW#1 well approximately 1 km north-west of the Marraat-1 drillsite. Drilling was continued in 1995 with 3 slim-hole wells (GANE#1, GANK#1 and GANT#1) and in the following year a full-scale exploration well (GRO#3) was drilled.

Field work has been carried continuously out by the Survey in part sponsored by EFP-funding from the Danish State and also by funds from the Greenland Home Rule Government and the Carlsberg Foundation. The combined Survey and exploration activities greatly increased the general petroleum geological knowledge of the region; however, as exploration entered the full-scale drilling phase it became evident that an improved understanding of reservoir development in the region was required.

In order to fulfil this need a project on reservoir modelling was initiated in 1996 by the Geological Survey of Denmark and Greenland (GEUS) with economic support from EFP-96 (50% economic contribution) and the Greenland Home Rule Authorities (25% economic contribution).

The primary objective of the project was to provide the framework for initial quantitative reservoir models from those parts of the Nuussuaq Basin which, based on present stratigraphic and structural data, seem to have the best exploration potential. Both existing and newly acquired data from geophysical, sedimentological, petrographical, petrophysical, geochemical and diagenesis studies have been used to characterise potential sandstone reservoirs on western Nuussuaq. It is anticipated that the results of the study will contribute to the planning of future exploration and GEUS activities in the region.

The main part of the project has focused on data and material from wells drilled by grønArctic Inc. as part of their exploration commitments. These wells are mainly located in a volcanic terrain characterised by abundant oil seeps and where little or nothing was known about the subsurface geology prior to drilling (Fig. 1). The volcanic terrain separates major sedimentary outcrop areas of Nuussuaq showing very different depositional environments. Sedimentological, geochemical and palynostratigraphical analyses of the sediments penetrated in the wells have therefore been essential in basin analysis. Main emphasis has been laid on the evaluation of diagenetic alterations with respect to reservoir properties of the GANT#1 core and on palynostratigraphical, lithological and petrophysical analyses of the GRO#3 well which encountered the so far thickest Cretaceous–Tertiary described section in the basin.

The project is closely linked with seismic studies in the Disko Bugt–Uummanaq Fjord region and geological field studies financed by the Greenland Homerule Authorities and modelling of maturity and subsidence in the Disko–Nuussuaq area financed by GEUS and EFP-95.

As part of the project all offshore and onshore wells relevant to petroleum exploration in western Greenland have been incorporated in the Danish national well data repository 'SAMBA' (Nielsen 1998).

This final report on the EFP-96 project 'Reservoirmodelling of western Nuussuaq' summarises the collection of all studies related to reservoir modelling of the Nuussuaq Basin and includes also reports made under other, related projects. These have been published as GEUS reports; a single paper has been accepted for publication elsewhere and all are included as appendices listed below:

Well data summary (SAMBA):

Nielsen, Å. 1998: Well data summary sheets: West Greenland onshore and offshore wells. GEUS Notat 09-EN-98-05.

Core analysis:

Andersen, G. 1996: Conventional core analysis on GANE#1 and GANE#1A cores, Eqalulik, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1996/117.

Andersen, G. & Jensen, M.K. 1997: Conventional core analysis on GANK#1 cores, Kuussuaq, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/84.

Organic geochemistry:

Christiansen, F.G., Bojesen-Koefoed, J., Nytoft, H.-P. & Laier, T. 1997: Organic geochemistry of sediments, oils, and gases in the GANE#1, GANT#1 and GANK#1 wells, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1996/23.

Bojesen-Koefoed, J., Christiansen, F.G., Nytoft, H.P. & Dalhoff, F. 1997: Organic geochemistry and thermal maturity of sediments in the GRO#3 well, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/143.

Bojesen-Koefoed, J.A., Christiansen, F.G., Nytoft, H.P. & Pedersen, A.K. in press: Oil seepage onshore West Greenland: evidence of multiple source rocks and oil mixing. Petroleum geology of Northwest Europe: proceedings of the 5th conference. London: The Geological Society.

Palynology:

Nøhr-Hansen, H. 1997a: Palynology of the boreholes GANE#1, GANK#1 and GANT#1 Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/89.

Nøhr-Hansen, H. 1997b: Palynology of the GRO#3 well, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/151.

Sedimentology:

Dam, G. 1996a: Sedimentology of the GANE#1 and GANE#1A cores drilled by grønArctic Energy Inc., Eqalulik, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1996/82.

Dam, G. 1996b: Sedimentology of the GANK#1 and GANK#1A cores drilled by grønArctic Energy Inc., Kuussuaq, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1996/83.

Dam, G. 1996c: Sedimentology of the GANT#1 core drilled by grønArctic Energy Inc., Tunorsuaq, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1996/96.

Diagenesis:

Kierkegaard, T. 1998: Diagenesis and reservoir properties of Cretaceous–Lower Tertiary sandstones: the GANT#1 well, western Nuussuaq, central West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1998/7.

Petrophysical evaluation:

Kristensen, L. & Dam, G. 1997: Lithological and petrophysical evaluation of the GRO#3 well, Nuussuaq, West Greenland, 2nd edition. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/156.

Geological setting and general stratigraphy

The West Greenland rifted continental margin developed during the opening of the Labrador Sea in Late Mesozoic–Early Cenozoic time. Along the continental break-up zone a number of rift basins developed that stretch all the way from the Labrador Sea to northern Baffin Bay (Chalmers & Pulvertaft 1993; Chalmers *et al.* 1993). In this region onshore exposures of Mesozoic–Lower Tertiary sediments only occur at Cape Dyer on Baffin Island, Canada (Burden & Langille 1990) and in central West Greenland on a number of islands and peninsulas between 69°N and 72°N (Fig. 1; Rosenkrantz 1970). While the deposits of Baffin Island have a limited distribution and exclusively consist of fluviatile sediments, the deposits of West Greenland include both marine and terrestrial sediments (cf. Pedersen & Pulvertaft 1992; Dam & Sønderholm 1994a; Dam & Sønderholm 1994b; Midtgaard 1996).

The sedimentary succession in West Greenland is in places 6–8 km thick of which only the uppermost 2.5 km lower Cretaceous (Albian) to lower Tertiary (Paleocene) succession is exposed (cf. Christiansen *et al.* 1995). The sediments are overlain by up to 2.5 km picritic hyaloclastites and continental flood basalts. The outcrops are bounded to the east by Precambrian basement against which Cretaceous sediments have a faulted contact (Fig. 1; Pedersen & Pulvertaft 1992). Seismic reflection lines and gravity maps indicate that the sediments constitute a continuous cover that can be followed into offshore areas to the north, west and south (cf. Whittaker 1996).

Non-marine strata referred to the Kome and Atane Formations of Cretaceous age crop out on eastern Disko and on eastern and north-eastern Nuussuaq. The non-marine sediments are fluvial in the southern, eastern and northern part of the region; westwards and north-westwards there is both a lateral transition in space and an upwards transition in time through delta plain deposits with coal in delta front deposits and horizons containing typical marine trace fossils and occasional marine bivalves and ammonites. In the south and east, the exposed non-marine sediments are of Albian-Cenomanian age, while to the west and north-west they are younger, in places possibly as young as early Campanian (Fig. 2; Pedersen & Pulvertaft 1992). In the Itilli area, along the north coast of Nuussuaq and on Svartenhuk Halvø, the Atane and Kome Formations give way to turbidite slope deposits, referred to as the Itilli and Umiivik successions (Fig. 2; Dam & Sønderholm 1994a; Dam 1997).

On Nuussuaq a major, regional Maastrichtian unconformity separates the Atane Formation from marine turbidite deposits comprising mudstones, sandstones and conglomerates of Late Cretaceous to Paleocene age (cf. Dam & Sønderholm 1994a; Nøhr-Hansen & Dam 1997). The marine deposits are well exposed along the south and north coasts and in the central part of Nuussuaq where they are referred to the Kangilia Formation (Rosenkrantz 1970). These deposits can be followed south across Nuussuaq to northern Disko and are unconformably overlain by shallow marine sandstones referred to the Agatdal Formation on central and northern Nuussuaq and by the Paleocene Quikavsak Member of the Upper Atanikerdluk Formation along the south coast of Nuussuaq (Koch 1959; Rosenkrantz & Pulvertaft 1969; Dam & Sønderholm 1998). The sandstones of the Quikavsak Member were deposited in an incised valley system.

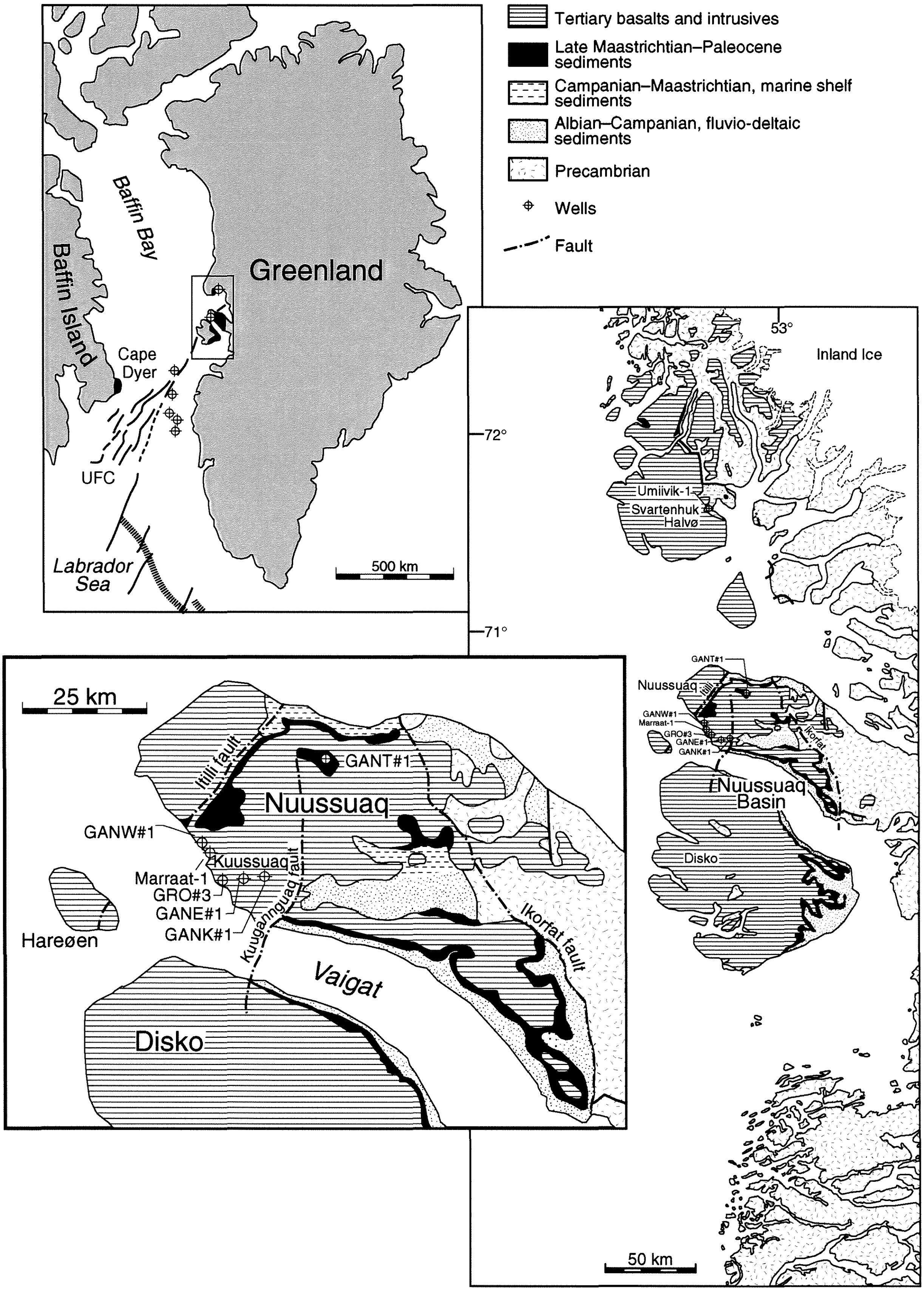

Figure 1. Geological map of central West Greenland showing location of wells in the area. Based on maps from the Geological Survey of Greenland. UFC: Ungava fault complex.

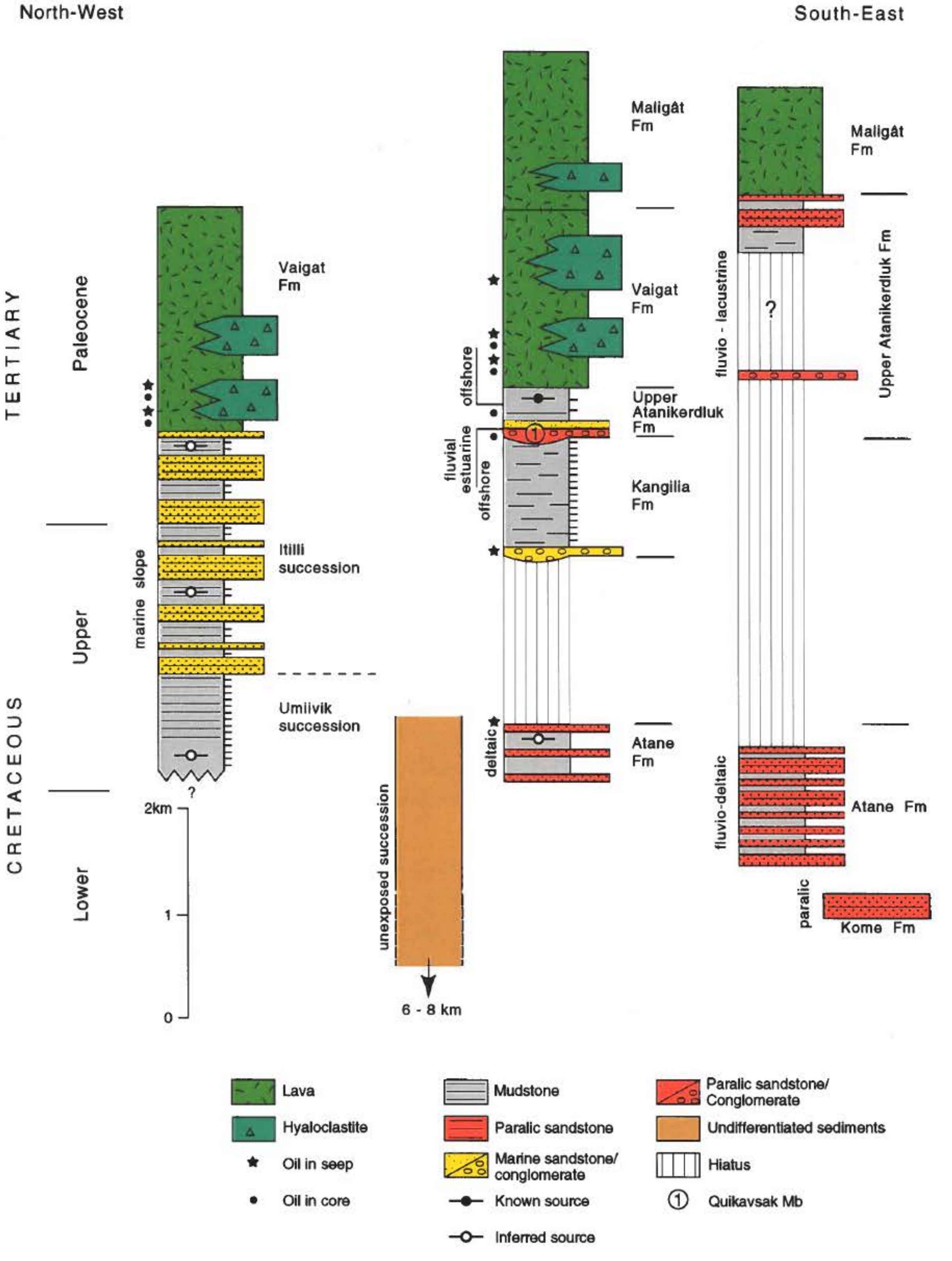

Figure 2. Simplified stratigraphy of Cretaceous–Paleocene successions from the Nuussuaq Basin, West Greenland, showing distribution of oil in seeps, oil in cores, known and inferred source rocks and reservoir rocks.

The incision of the Quikavsak Member valley system followed a tectonic episode associated with major uplift of the basin. It is suggested that this tectonic episode reflects the arrival of the North Atlantic mantle plume (Dam *et al.* 1998).

Valley incision was followed by rapid major subsidence associated with extensive volcanism. The volcanic rocks consists of up to 2.5 km of picritic hyaloclastites and flood basalts (e.g. Pedersen 1985; Pedersen 1993). Volcanism began at 60.5 ± 0.5 Ma (Storey *et al.* in press).

Geophysical surveys

As part of the intensified efforts in promoting the West Greenland offshore regions to the oil-industry several multi-channel seismic surveys have been carried out in recent years (Chalmers *et al.* 1995; Christiansen *et al.* 1995; Christiansen *et al.* 1996a). Interpretation of these surveys and new aerogravity data (Forsberg & Brozena 1993) will lead to improvements in the interpretation of the basin configuration and to a better understanding of where hydrocarbons may have been generated and where future exploration could best be carried out.

Basin configuration and structure

The new geophysical surveys indicate that the sedimentary pile in the western part of the coastal regions of the Disko–Nuussuaq area and possibly further north is in the order of 6–8 km thick and thus much thicker than the previously known 2–3 km succession exposed onshore (Christiansen *et al.* 1995). Interpretation of gravity data suggests that maximum depth to basement is in the order of 8–10 km in the western part of the region, whereas it is much shallower under eastern Disko and Disko Bugt where maximum depths to basement are between 2 and 3 km (Chalmers in press, Chalmers *et al.* in press).

Although the sequence of events that created the Nuussuaq Basin is not fully understood, the deep, western basin possibly represents a rift basin – a hypothesis supported by the Moho being shallow in this area. The age and sedimentary fill of this basin is conjectural. The shallower and areally more extensive basin, into which the Cretaceous Atane Formation and its correlatives were deposited, could represent the thermal subsidence phase of this rifting episode. Large, rotated fault blocks, 2 to 20 km wide, were created during an episode of rifting in latest Maastrichtian time (Rosenkrantz 1970; Pulvertaft 1989; Dam & Sønderholm 1998). The major faults trend NW–SE and N–S. Minor WNW–ESE trending faults, possibly related to this phase, are apparent especially on gravity interpretations (Chalmers in press, Chalmers *et al.* in press). This direction coincides with a trend of shear zones observed in the basement to the east.

Renewed faulting in the basin along a N–S (reactivated? Kuugannguaq fault) and a NE–SW (Itilli fault) trend was probably related to Eocene movements along the major Ungava fault system farther south-west (Chalmers *et al.* 1995; Whittaker *et al.* 1997) and the whole region was exposed to uplift in the order of 1–2 km during the Neogene.

Petroleum prospectivity

Based on seismic facies, source rock maturity and general structural style, the region has been provisionally divided into six provinces with different implications for prospectivity (Fig. 3).

Seismic facies – source rocks, reservoirs and seals

The seismic surveys in the region reveal two seismic facies with distinctly different internal reflection patterns (J.A. Chalmers, personal communication, 1997).

Facies 1 is characterised by relatively strong and laterally continuous reflections. Onshore exposures suggest that facies 1 either represents fluvio-deltaic sandstones, mudstones and coals (Atane Formation) or Cretaceous and Paleocene marine sandstones and mudstones which could provide both source rocks, reservoirs and seals.

Facies 2 is distinguished by weak and discontinuous reflections and probably represents thick successions of monotonous fluviatile sandstones comparable to those exposed on eastern Disko. Areas characterised by this facies have a very low exploration potential as laterally extensive source rocks or seals are probably not present.

Prospective areas

The main prospective areas extend from north-western Disko, across central Nuussuaq east of the Itilli fault and somewhat further to the north into Uummannaq Fjord (Fig. 3). The region is characterised by large, rotated fault blocks which could provide structural traps. The sedimentary succession is thick, mostly more than 5 km and the area includes the main surface indications of oil found so far, and these comprise 5 different types (Bojesen-Koefoed *et al.* in press). The ages, depositional environment and lateral extent of the source rocks responsible for these oils are largely unknown. However, for them to be mature, they have to be buried at a minimum depth, implying that they will not be mature where depth to basement is low. A somewhat arbitrary depth to basement of approximately 1–1.5 km has been used to divide possible prospective areas from non-prospective.

The seismic facies suggest the presence of interbedded marine sandstones and mudstones (seismic facies 1) which could provide both source rocks, reservoirs and seals.

The prospective area may continue further south on western Disko, but in this region models are based solely on surface observations and gravity modelling (Fig. 3). Conclusions are thus much less reliable than for the main prospective area. Basement is between 2 and 4 km below sea level and mature source rocks, structural traps, reservoirs and seals could all be present. However, the intensity of volcanism may have been too intense, as many of the eruptions that sourced the flood basalts on Disko probably occurred in this region (Chalmers in press; Chalmers *et al.* in press).

Areas with low exploration potential

On eastern Nuussuaq, eastern Disko and in Disko Bugt, the depth to basement is generally less than 2 km and possible source rocks would thus not be mature (Fig. 3) which in itself is suspect (Chalmers in press). In Disko Bugt the seismic surveys furthermore suggest that the

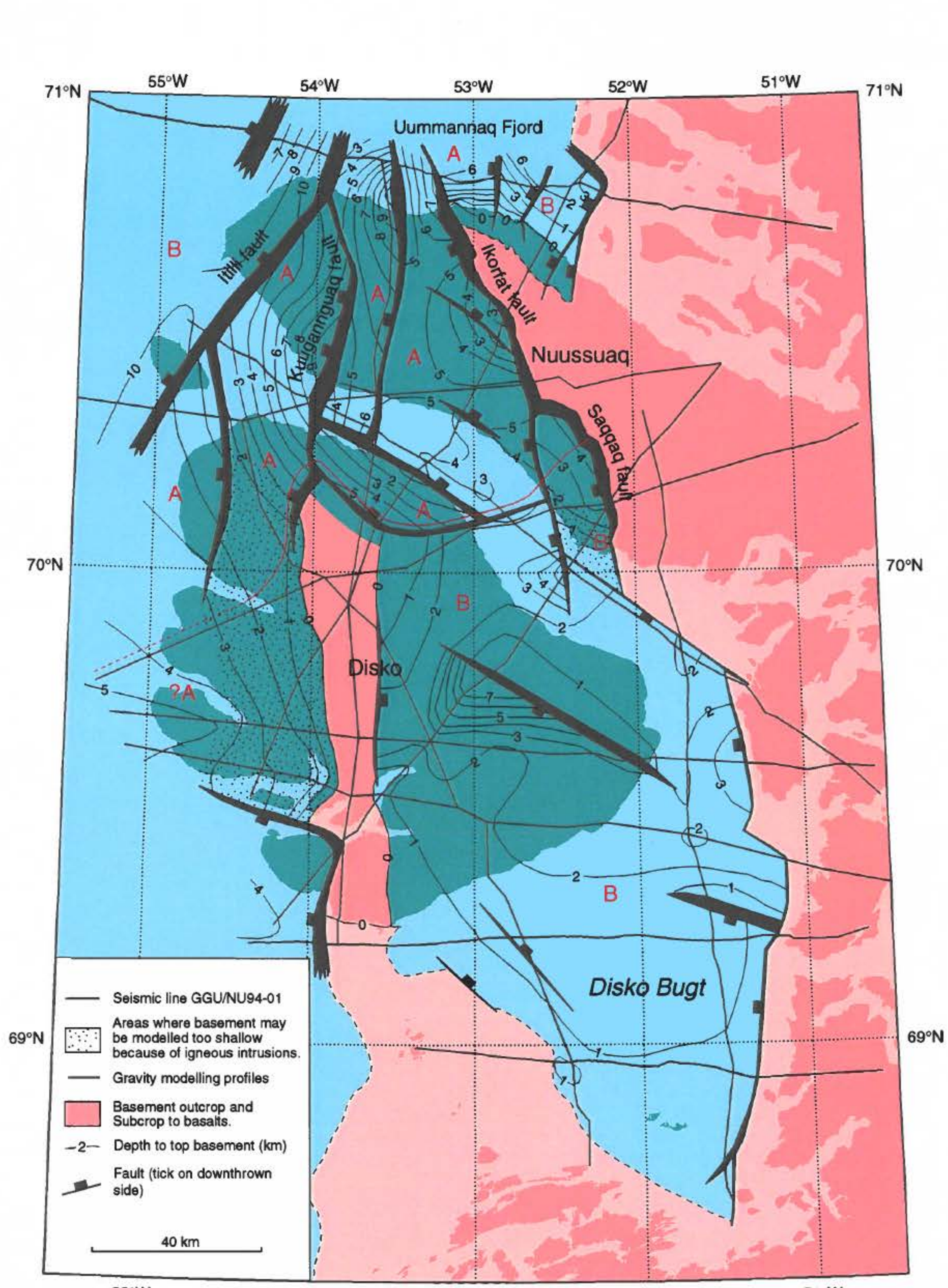

Figure 3. Depth to basement map of Nuussuaq and Disko based on gravity modelling showing prospective areas (A) and areas of low exploration potential (B) discussed in the text. Modified from Chalmers (in press) and Chalmers *et al.* (in press).

sediments are probably very uniform in lithology (seismic facies 2) and it is therefore unlikely that reservoirs, source rocks and seals can be found together.

In a small area under eastern Disko depth to basement is calculated to be more than 3 km (Chalmers in press) and possible source rocks could thus be mature; however, this interpretation is very uncertain. Oil generated here could migrate laterally into traps along the eastern flank of the Disko gneiss ridge and under eastern Disko (Fig. 3).

North-west of the Itilli fault, the presence of oil seeps at surface indicates mature source rocks in the region or migration of oil from offshore areas. However, potential reservoir rocks are probably buried to deep to be economic targets at this stage of exploration.

Oil seepage and source rock intervals onshore West Greenland

Oil seeps

Since 1992 widespread oil seepage and staining have been observed in lavas and hyaloclastites in the lower part of the volcanic succession and in the top of the sedimentary succession throughout most of the area from northwestern Disko in the south, through western Nuussuaq and to southern Svartenhuk Halvø in the north (Fig. 4; GHEXIS 1997; Bojesen-Koefoed *et al.* in press). Seepage and staining mainly occur within vesicular lava flow tops, and are often associated with mineral veins in major fractures (Bojesen-Koefoed *et al.* in press), but have also been recorded in Paleocene sediments particularly in the GANE#1 and GANK#1 cores (Christiansen *et al.* 1996b; Dam 1996a; Dam 1996b).

Organic geochemical analyses suggest the existence of at least five distinct oil types (Bojesen-Koefoed *et al.* in press):

(1) a waxy oil which, on the basis of the presence of abundant angiosperm biological markers, is interpreted as generated from deltaic Paleocene mudstones (Marraat type);
(2) a waxy oil, probably generated from coals and shales within the Cretaceous Atane Formation (Kuugannguaq type);
(3) a low to moderately waxy oil possibly generated from presently unknown Cenomanian–Turonian marine mudstones (Itilli type);
(4) a low wax oil of marine, possibly lagoonal or saline lacustrine origin (Eqalulik type);
(5) a waxy oil with biological marker characteristics different from both the Kuugannguaq and Marraat oil types, probably generated from Campanian mudstones (Niaqornaarsuk type).

Moreover, a strongly biodegraded oil seep was discovered for the first time in sedimentary outcrops at Asuk on northern Disko during the 1997 field season (Fig. 4). The oil seep occurs in sandstones of the mid-Cretaceous Atane Formation just underneath the unconformity separating the sandstones from overlying Paleocene marine mudstones.

The Marraat and Itilli type oils have a relatively large areal distribution, whereas the Kuugannguaq, Eqalulik and Niaqornaarsuk types show an areally limited distribution (Fig. 4).

The *Marraat oil type* is abundant in surface seeps throughout an at least 10×15 km area around Marraat. Surface seeps of this type have also been recorded on the north coast of Disko and on Hareøen (Fig. 4).

The *Kuugannguaq oil type* is found as surface seeps at a few localities within and east of the Kuugannguaq fault zone, near the mouth of the Kuugannguaq valley on the north coast of Disko (Fig. 4).

The *Itilli type* occurs as surface seeps at a number of localities west of the Itilli fault zone in the westernmost part of Nuussuaq. Discoveries are primarily along the south-west coast of Nuussuaq, but one sample has been collected on the north coast, and a few seeps from the

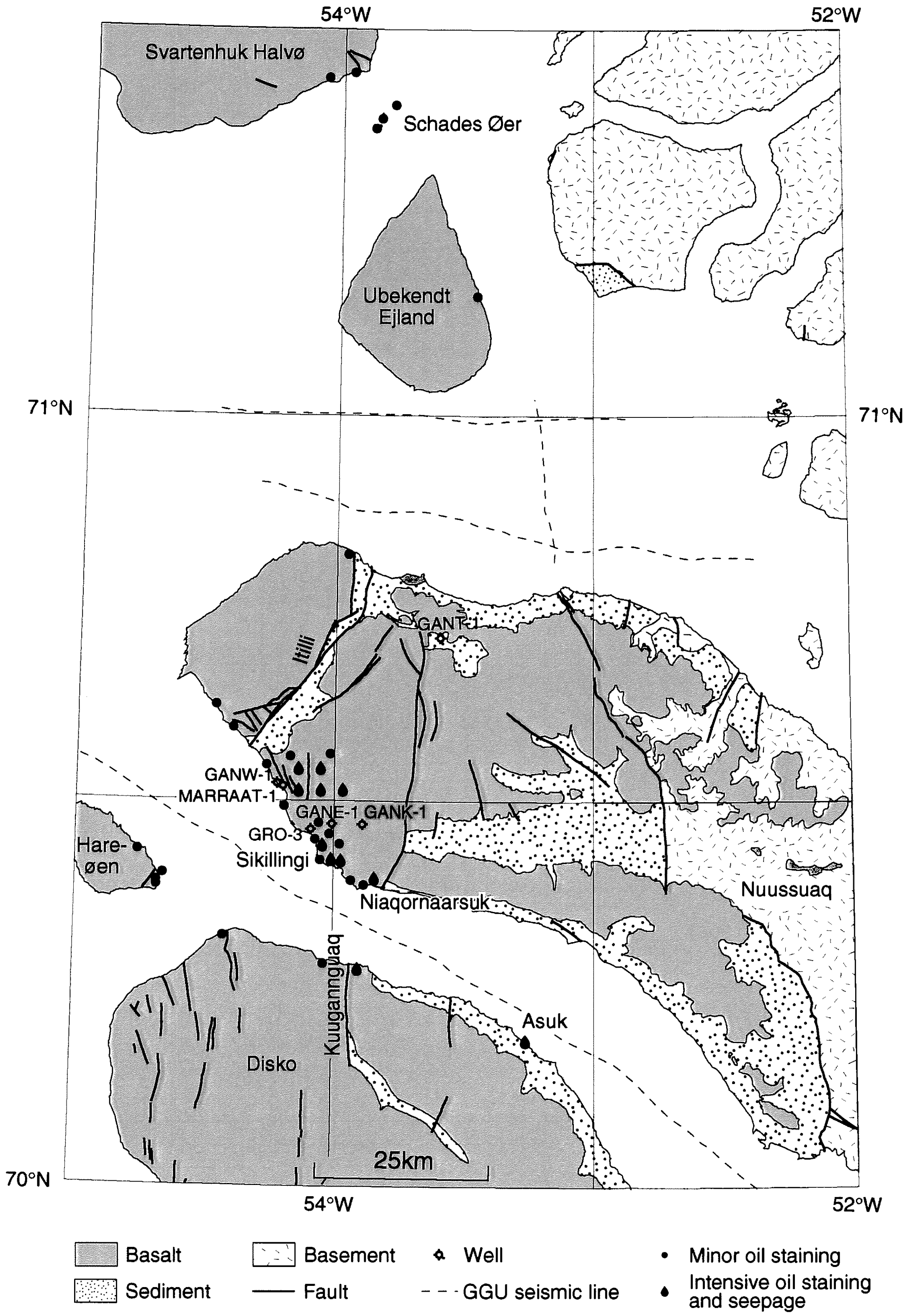

Figure 4. Map of the Disko–Svartenhuk Halvø region showing the distribution of localities with seepage and staining of oil. From GHEXIS (1997).

Kuugannguaq valley near the north coast of Disko yield biological marker distributions similar to those of the Itilli oil type (Fig. 4).

In its pure state, the *Eqalulik oil type* is only known from Paleocene sediments in the GANE#1 well on Nuussuaq where it occurs separated from the Marraat-type oil which is present in the hyaloclastic part of the core. Mixtures of the Marraat and Eqalulik oil types in varying proportions are found as surface seeps in a relatively large area between GRO#3 and Niaqornaarssuk on the south coast of Nuussuaq (Fig. 4).

The *Niaqornaarsuk oil type* is only found as surface seeps in a small area, separated from the area in which mixtures of the Marraat and Eqalulik oil types occur, immediately west of the Kuugannguaq fault zone near Niaqornaarsuk on the south coast of Nuussuaq (Fig. 4).

Source rock intervals

Only a few source rock intervals are presently known from wells and outcrops onshore West Greenland (Fig. 2).

Selandian (Upper Paleocene) turbidite mudstones from the uppermost 80 m of sediments in the GRO#3 and GANE#1 wells have TOC-values between 2.4 and 4 wt.% and HI-indices between 97 and 217. The mudstones contain abundant higher land plant debris and GCMS-analyses show that the biological marker distribution closely correlates with the Marraat oil (Bojesen-Koefoed *et al.* in press). These mudstones are not known from outcrops.

During fieldwork in 1997 a lacustrine mudstone within the Lower Paleocene Quikavsak Member was sampled along the south coast of Nuussuaq. This mudstone shows TOC-values between 6.7 and 11 wt.%, and HI-indices between 144 and 174. GCMS-analyses are currently undertaken in order to test if biological marker distribution correlates with any known oil type.

Lower Campanian–Danian (Lower Paleocene) turbidite mudstones from the interval between 400 m and 1170 m in the GRO#3 well have TOC-values between 1.2 and 5.9 wt.% and HI-indices between 85 and 139 (Bojesen-Koefoed *et al.* 1997). Although the analysed mudstones from GRO#3 and GANT#1 show a limited hydrocarbon generation potential there are strong similarities in biomarker composition between the Niaqornaarsuk oil type and the Campanian mudstones.

Furthermore, the biomarker distribution of the known oil types suggest the presence of a Cenomanian–Turonian marine source rock and it is also likely that oils have been generated from coals and shales within the Cretaceous Atane Formation.

Potential reservoir intervals

A generalised stratigraphical scheme of the Nuussuaq Basin, showing potential source rocks, reservoir rocks and known oil seeps and oil staining in cores is shown in Figure 2. Potential reservoir rocks occur in the Atane, Kangilia, and Upper Atanikerdluk Formations and within the Itilli succession.

Atane Formation

Strata referred to the Cretaceous Atane Formation crop out on eastern Disko and eastern and southern Nuussuaq (Fig. 1). In the southern and eastern part of the region sediments are fluvial; westwards and north-westwards there is a transition both in space and time through delta plain deposits with coal into delta front deposits with horizons containing typical marine trace fossils and occasional marine bivalves and ammonites. In the south and east, the exposed non-marine sediments are of Albian–Cenomanian age, while to the west and north-west they are younger, in places possibly as young as early Campanian (Pedersen & Pulvertaft 1992).

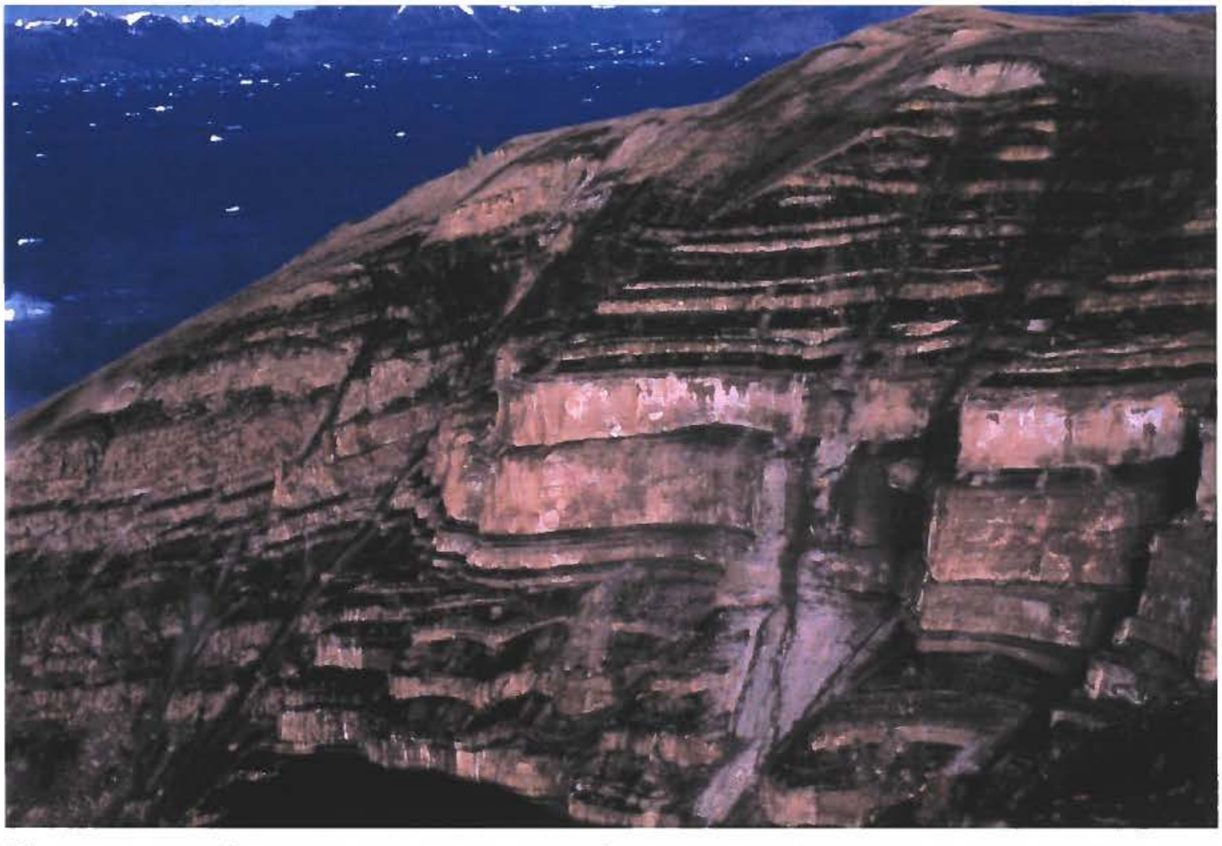

Figure 5. View of typical delta plain and delta front deposits of the Atane Formation exposures along the north coast of Nuussuaq. Cliff section is approximately 300 m high.

In the eastern part of Disko the Atane formation consists of thick alluvial flood plain deposits arranged in multistorey, laterally amalgamating, medium to coarse-grained sheet sandbodies; mudstone intervals are rare and laterally discontinuous (Pedersen & Pulvertaft 1992). Towards north-west, the flood plain sandstones grade into delta plain and delta front deposits (Fig. 5). Distributary delta plain channel sandstones form 10–30 m thick, medium-grained to very coarse-grained sheet and ribbon sandstones. The ribbons are up to 100 m wide, whereas the width of the sandstone sheets may exceed 500 m (Olsen 1993). The delta front sequences form 5–15 m upward-coarsening sheet sandstones formed by progradation of successive delta lobes. The uppermost part of the coarsening-upward sandstones consists of fine-grained sandstones (Pedersen & Pulvertaft 1992; Olsen 1993). The sands of the Atane Formation are loose to slightly consolidated and seem to form excellent potential reservoir units; however, no petrographical or petrophysical analyses have yet been performed on these sands.

Kangilia Formation

Sediments referred to the Kangilia Formation of Late Maastrichtian–Early Paleocene age crop out along the northern and southern coasts of Nuussuaq and on central Nuussuaq and have also been encountered in the GANT#1 and GRO#3 wells (Fig. 1; Dam 1996c; Kristensen & Dam 1997). The formation is separated from the sediments below by a major tectonically-

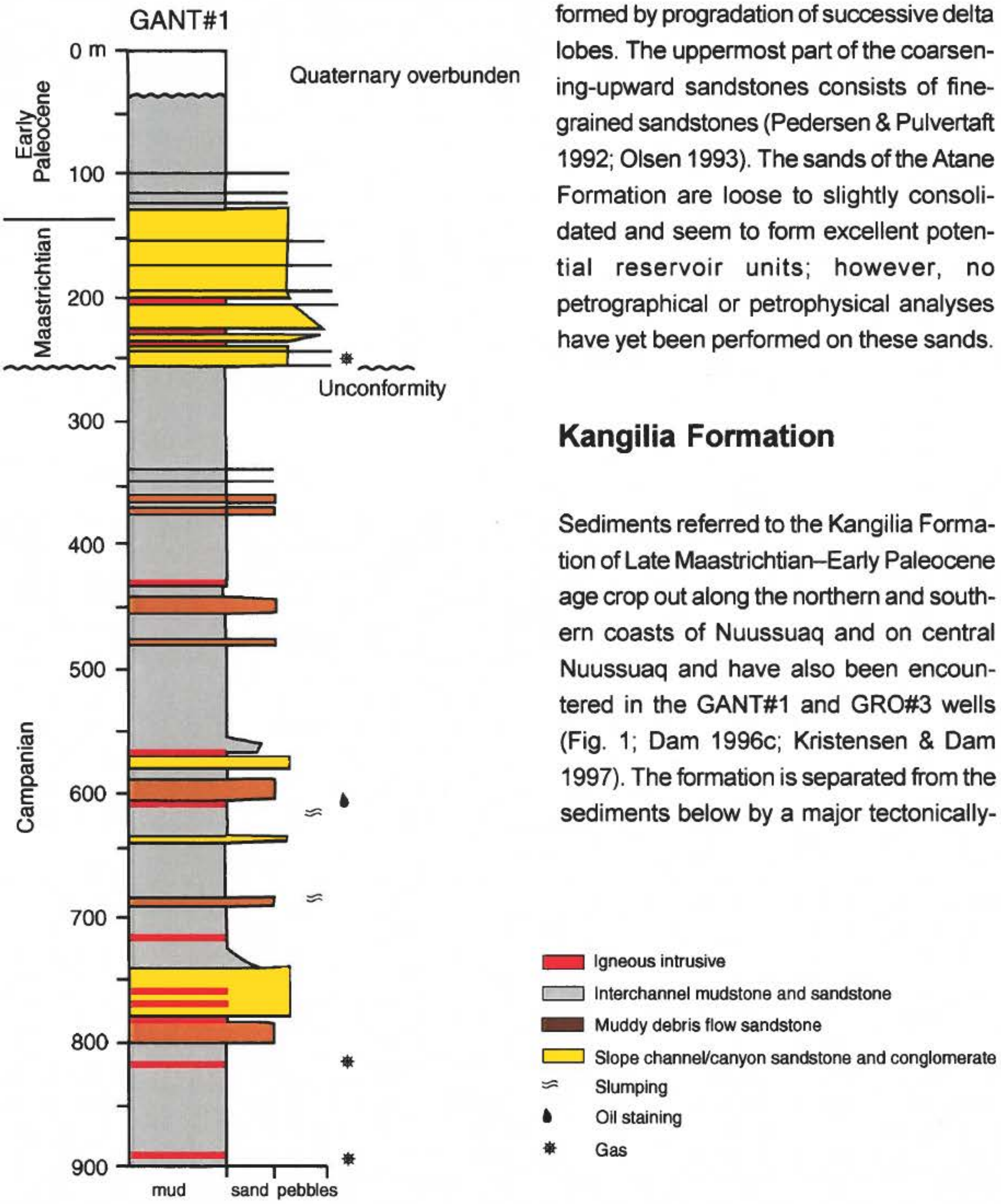

Figure 6. Generalised sedimentological log from the GANT#1 core. Modified from Dam (1996c).

induced unconformity that has been recognised throughout the basin (Dam & Sønderholm 1998; Dam *et al.* 1998). The formation is mudstone-dominated and is generally without any reservoir potential. However, at the north coast of Nuussuaq the basal unconformity is succeeded by a submarine canyon conglomerate-sandstone unit referred to as the Conglomerate Member (Rosenkrantz 1970; Christiansen *et al.* 1992). At this locality it is 20–50 m thick but in the GANT#1 well, approximately 6 km further to the south, it is 160 m thick (Fig. 6; Dam 1996c; Nøhr-Hansen 1997a). The Conglomerate Member may be coeval with the Sonja Member in Agatdalen on central Nuussuaq. The Sonja Member is an about 50 m thick, lenticular unit which can be traced laterally for approximately 1 km. It consists of a gneiss boulder conglomerate at the base grading upward into interbedded sandstones, shales and conglomerates. Palaeocurrent indicators suggest that the N–S line from the coastal exposures to the GANT#1 well represents a cross-section of the submarine canyon suggesting that it was at least 6 km wide, probably exceeding 10 km. If the Conglomerate Member correlates with the Sonja Member this conglomerate-sandstone unit may be followed for at least 25 km in a down-stream, westerly direction from Agatdalen.

Conventional core analysis of the Conglomerate Member in GANT#1 reveals porosities from 5.7 to 17.5% and permeabilities from 0.1 to 90.7 mD (Kierkegaard 1998). Two *c.* 12 m thick less lithified sandstone units in the upper part of the Conglomerate Member show good reservoir properties with porosities from 12.1 to 18.8 % and permeabilities from 16.6 to 90.7 mD indicating that the Conglomerate Member is a potential reservoir unit in large areas on central and northern Nuussuaq (Kierkegaard 1998).

In the GRO#3 well the Kangilia Formation is 240 m thick and consists of three heterolithic sandstone units, 40–80 m thick, separated by 10 m thick mudstone intervals. The heterolithic sandstones were probably deposited as turbidites in slope channels. A petrophysical evaluation of the GRO#3 well suggests porosities from 8% to 10% of the sandstones (Kristensen & Dam 1997).

Itilli succession

Sediments referred to as the Itilli succession crop out in the Itilli valley on western Nuussuaq along the rivers Ukalersalik, Anariartorfik, Pingunnguup Kuua and Ilugissorsuaq (Figs 1, 7; Dam & Sønderholm 1994a) and they have been drilled in the GRO#3 well (Kristensen & Dam 1997). The lower and upper boundaries of the succession are not exposed in the Itilli valley where the thickness is estimated to be in excess of 2500 m. In the GRO#3 well the uppermost 500 m of the succession has been dated to Coniacian–Campanian on the basis of palynomorph stratigraphy (Nøhr-Hansen 1997b); the underlying 1.5 km does not reveal any palynomorphs due to thermal alteration. The age of the outcrop section is somewhat uncertain, as palynomorphs are degraded due to deep burial followed by inversion and hydrothermal activity along the Itilli fault zone but a Campanian–Maastrichtian age is suggested for part of the succession (cf. Nøhr-Hansen 1996).

In the Itilli valley the succession consists of mudstone, thinly interbedded sandstone and mudstone and chaotic beds encasing up to 50 m thick and 1–2 km wide channelised sandstone

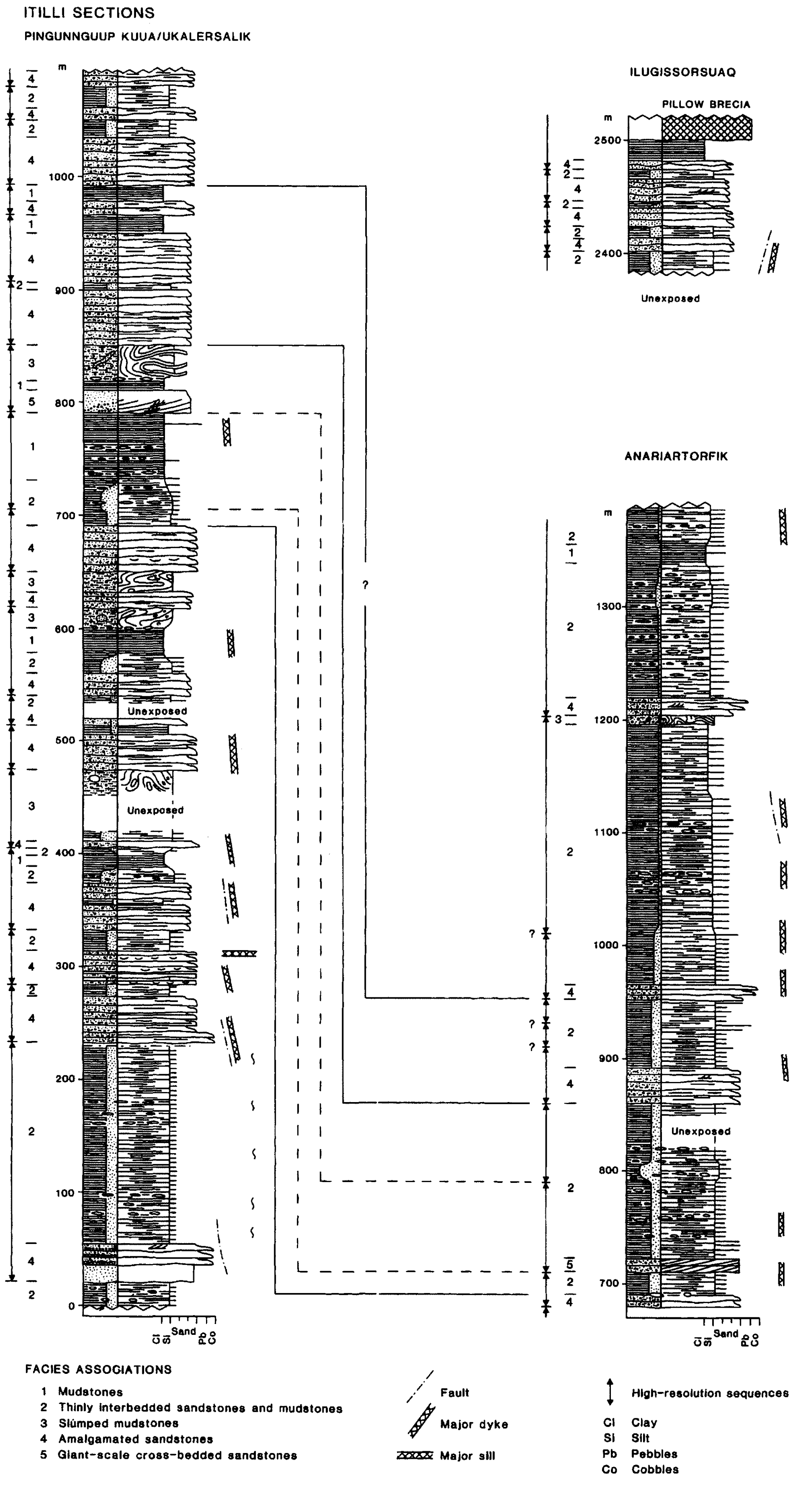

Figure 7. Generalised sedimentological log through the Itilli slope succession. From Dam & Sønderholm (1994a).

Figure 8. Amalgamated medium to coarse-grained sandstones deposited in a slope channel in the Itilli area. Cliff section 45 m high.

units deposited in a slope apron setting (Fig. 8; Dam & Sønderholm 1994a). The individual turbidite channel sandstones are medium-grained to very coarse-grained but generally show an overall fining-upward trend into the overlying mudstone facies. The most coarse-grained turbidite channel sandstones occur at the base of the exposed section. Both porosities (1.9–9.8%) and permeabilities (0.01–0.36 mD) are low. The low values are related to stalk-like illite growth in intergranular pores and high-temperature pressure solution of quartz grains due to hydrothermal activity along the Itilli fault zone (Preuss 1996). However, both porosities and permeabilities are expected to increase away from the Itilli fault zone.

In the GRO#3 well the Itilli succession is similarly developed (Kristensen & Dam 1997, app. 2). The drilled succession is more than 2 km thick and comprises mudstone, interbedded sandstone and mudstone and sandstone intervals showing a blocky log pattern. The sandstone units are from a few metres to *c.* 100 m thick and the gamma-ray log pattern suggests that they are sharply based and often show an overall fining upward trend. The thicker sandstone units are usually grouped together. The most coarse-grained sandstones occur in the lower part of the succession as in the Itilli valley. Cores are not available from the GRO#3 well but the log-pattern is very similar to a hand-held gamma-ray survey from the Itilli valley (F. Dalhoff, personal communication, 1997) suggesting that the Itilli succession in the GRO#3 well was deposited in a slope apron environment similar to the succession exposed in the Itilli valley. Evaluation of sandstone porosities has been carried out using the density log and show values between 5% and 10% (Kristensen & Dam 1997).

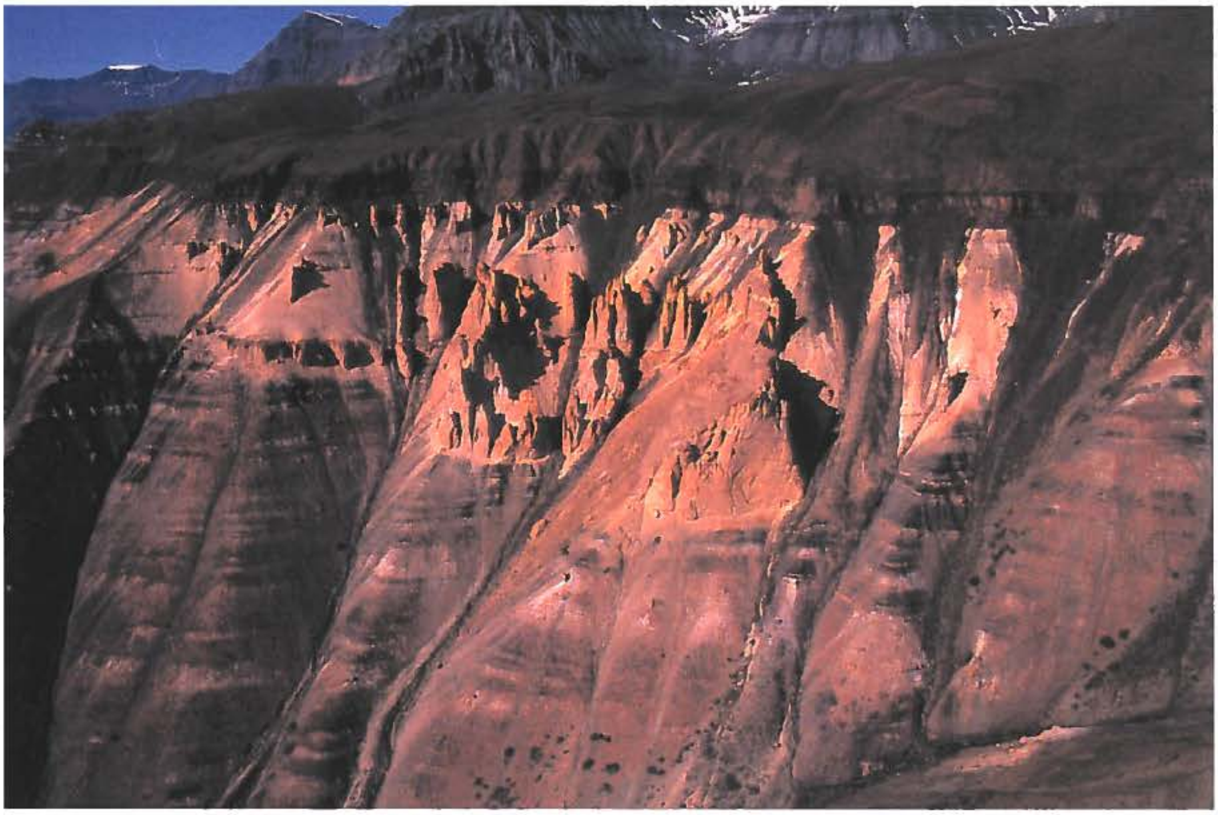

Figure 9. Incised valley fill sandstone of the Quikavsak Member. The valley is 190 m deep and cuts into mid-Cretaceous deltaic deposits of the Atane Formation.

Quikavsak Member

Sediments referred to the Quikavsak Member of Danian–Early Selandian age crop out along the south coast of Nuussuaq (Koch 1959; Dam & Sønderholm 1998) where they are separated from underlying sediments by a tectonically-induced, regional unconformity which is associated with major uplift of the basin (Fig. 9; Dam & Sønderholm 1998). These sediments represent a palaeovalley system including at least 5 synchronous valleys that each are 1–2 km wide and up to 190 m deep. The valley fills consist of loosely cemented very coarse-grained to medium-grained sandstones deposited in a fluvial to estuarine environment (Dam & Sønderholm 1998).

Lithostratigraphical and palynostratigraphical correlation suggest that coeval deposits have been encountered in both the GANE#1 and GRO#3 wells (Dam 1996a; Kristensen & Dam 1997; Nøhr-Hansen 1997b; Nøhr-Hansen 1997a).

In the GANE#1 well the uppermost *c.* 20 m of the member was penetrated and cored showing thickly bedded coarse-grained to very coarse-grained sandstone beds deposited from channelised, sand-rich turbulent flows in a slope or canyon environment (Dam 1996a). Both porosities (6.4–20.6%) and permeabilities (0.04–9.1 mD) of the penetrated intervals vary from poor to good. Scattered oil impregnations occur in this interval and 30 metres above it (Christiansen *et al.* 1996b; Dam 1996a).

In the GRO#3 well, which is situated 4 km WSW of the GANE#1 well, the uppermost part of the drilled sedimentary succession has been correlated with the GANE#1 well (Kristensen & Dam 1997; Nøhr-Hansen 1997a; Nøhr-Hansen 1997b) suggesting that the sandstones of the

GANE#1 and GRO#3 wells were deposited within the same depositional complex. In the GRO#3 well the Quikavsak Member is 294 m thick suggesting that deposition took place in a canyon rather than in a slope channel. The palynological dating propounds that this canyon was coeval with the major incised valley system of the Quikavsak Member exposed along the south coast of Nuussuaq. If this correlation is correct, the Quikavsak valley system could have sourced the canyon and a major unconformity may be present at the base of the Quikavsak Member in GRO#3. The change from an incised valley system to a slope canyon probably takes place along the Kuugannguaq fault (Fig. 1). A petrophysical evaluation of the GRO#3 density log suggests that the Quikavsak Member sandstones exhibit porosities between 10 and 15% (Kristensen & Dam 1997).

Diagenesis

Although potential reservoir intervals are common in the Nuussuaq Basin (see section above), preliminary investigations in the western part of the basin suggest that actual reservoir characteristics are highly variable and mostly rather poor, i.e. show low porosities and permeabilities (Preuss 1996). These investigations furthermore suggested that the deteriorated reservoir properties were mainly caused by a complex suite of diagenetic alterations. However, most of the preliminary analyses were carried out on samples collected close to the Itilli fault which is characterised by strong hydrothermal activity. It was therefore decided to conduct more detailed diagenetic studies on some of the most prospective reservoir intervals on western Nuussuaq in order to elucidate whether the reservoir problems could be anticipated to be of local or regional character.

To achieve high-quality samples within a well established stratigraphic framework, two fully cored wells – GANT#1 and GANE#1 – were selected for the study (Fig. 1; Kierkegaard 1998). Emphasis was laid mainly on the Campanian–Lower Paleocene turbiditic conglomerate and sandstone packages encased in mudstone found in the GANT#1 well which can be correlated with the nearby coastal sections in the Annertuneq–Kangilia region on northern Nuussuaq (Fig. 1; cf. Nøhr-Hansen & Dam 1997). The GANE#1 well provides a section through Upper Paleocene turbiditic sandstone units encased in mudstone which thus furnishes a complementary and stratigraphically higher section to that found in GANT#1. There are, however, no exposed correlative outcrops in the vicinity of GANE#1 which could provide further details on the cored section.

Sedimentological and palynological studies of the two wells have been accomplished to produce a firm environmental and stratigraphic basis for the diagenetic studies (Dam 1996c; Dam 1996a; Nøhr-Hansen 1997a). Conventional core analysis of samples from GANE#1 and GAN#1 have provided 172 porosity/permeability measurements together with spectral core gamma logs (Andersen 1996; Andersen & Jensen 1997). Twenty-four porosity/permeability analyses have been carried out on GANT#1 (Kierkegaard 1998).

Diagenesis studies of GANT#1

The main purpose of the studies have been to determine the diagenetic and detritus factors that control the present porosity and permeability variations occurring in the Cretaceous–Lower Paleocene succession of western Nuussuaq.

The GANT#1 well drilled through 901 m of sediments which are penetrated by 15 intrusions (Fig. 6; Dam 1996c) . A major, regional unconformity separates the upper 256 m of mudstones, coarse-grained sandstones and conglomerates of Maastrichtian–Early Paleocene age (Kangilia Formation) from a lower 645 m thick un-named succession comprising mudstone and medium-grained sandstone of Early to Late Campanian age (Dam 1996c; Nøhr-Hansen 1997a).

Detrital composition of sandstones

The sandstones are classified as subarkoses and are generally poorly sorted (Fig. 10); however, the post-Campanian sandstones above the unconformity seem to be better sorted and contain only little, if any, detrital clay. Feldspars, including both K-feldspar (mostly microcline) and plagioclase generally in equal amounts, are found both as unaltered and strongly sericitised grains. Lithic fragments are dominated by mudstone clasts. Compaction deformation, especially of the mudstone clasts, is the most significant alteration of the lithic fragments.

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

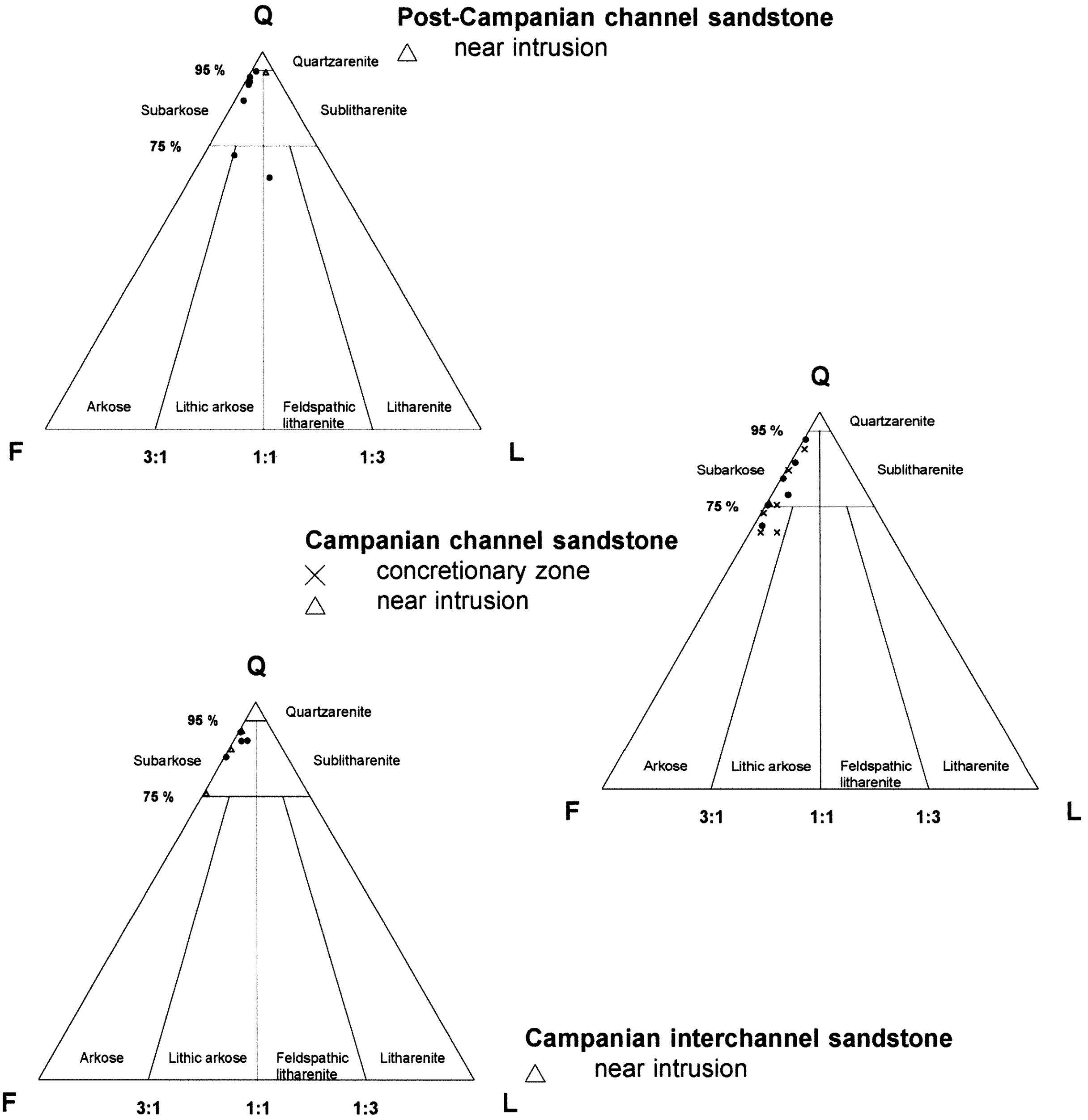

Figure 10. Sandstone classification according to the system by Folk (1968). Q: quartz (excluding chert), F: feldspar and rock fragments, L: lithic fragments includ mudstone clasts and chert. Mg-siderite aggregates are not included in the classification.

Diagenetic alterations

The unconformity at 256 m can be traced throughout the Nuussuaq Basin (Dam & Sønderholm 1998). This unconformity is interpreted to separate two distinct diagenetic stages of which the first only affects the Campanian deposits and the second the combined Campanian–Paleocene succession (Fig. 11).

		Campanian burial	Post-Campanian burial
Shallow burial	Apatite	–	
	Pyrite framboids	–	–
	Siderite type 1	–	–
	Early quartz	–	–
	Mixed-layer clay	–	– --?--
	Ferroan carbonate	–	
	Calcite		–
Deep burial	Feldspar dissolution		–
	Kaolinite		–
	Albite		–
	Third generattion quartz		–
	Siderite type 3		?
	Ankerite		–
	Pyrite concretions		–
	Compaction		

Figure 11. Paragenetic sequence of diagenetic events during the Cretaceous and Paleocene.

The Campanian diagenetic stage is characterised by growth of apatite, pyrite, siderite, quartz and mixed-layer clay which all formed during shallow burial in a marine, eogenetic environment (Fig. 11).

This stage is followed by cementation of the sandstone beds with ferroan carbonate forming conspicuous concretionary zones. These zones are only found in the Campanian sedimentary succession and are characteristically absent in the section overlying the unconformity. The amount of ferroan carbonate in the carbonate-cemented beds represents pre-cement porosity and varies from 26 to 40%.

The development of the concretionary zones are probably related to the formation of the major erosional unconformity recognised at 256 m in the well (Fig. 2). This conclusion is supported by the fact that the zones only occur in the Campanian sandstone beds, and that oxygen and carbon stable isotopes suggest that they formed under the influence of meteoric water. Furthermore, their development is succeeded by the formation of pyrite, siderite, 2nd generation quartz overgrowths, mixed-layer clay and calcite (Fig. 11), which are all considerated as phases developed in sediments influenced by evolved marine pore waters during shallow Maastrichtian–Paleocene burial.

Deeper burial diagenetic changes include feldpar dissolution and formation of secondary porosity followed by growth of kaolinite, albite, chlorite, 3rd generation quartz, siderite, ankerite and concretionary pyrite. The changes affect both the post-Campanian sandstones and the Campanian sandstones which are not cemented by ferroan carbonate and they mainly took place in detrital intragrain positions since most of all primary porosity was obliterated by compaction and the preceding diagenetic alterations (Kierkegaard 1998).

Reservoir conditions

Conventional core analyses on 19 plugs of partly cemented sandstone units from GANT#1 reveal a range in porosity from 0,60 to 17,5% and in permeability from 0,007 to 33,8 mD. The permeability is generally low (<10 mD) but the porosity of the post-Campanian sandstones is slightly increased compared to Campanian sandstones (Table 1). Nevertheless, two less lithified, approximately 12 m thick sandstone units located in the upper part of a Late Maastrichtian submarine canyon conglomerate unit reveal porosities varying from 12.1 to 18,8% and permeabilities varying from 16,6 to 90,7 mD (Table 1). The GANE#1 and GANE#1A cores from the south coast of Nuussuaq provide a section through Upper Paleocene turbiditic sandstone units encased in mudstone which thus furnish complementary and stratigraphically higher sections to that found in GANT#1. However, porosities and permeabilities of the GANE#1 and GANE#1A cores are low with an aritmetric average of 6.4% and 1,46 mD, respectively (Andersen 1996).

Table 1. *Range of porosities and permeabilities (perm.) for Campanian and Upper Maastrichtian–Paleocene sandstones.*

	Campanian sandstones		Post-Campanian sandstones	
	Porosity (%)	Gas perm. (mD)	Porosity (%)	Gas perm. (mD)
Conventional core analysis	4.92–13.73	0.106–4.05	5.21–17.45	0.112–33.8
Spot analysis			12.11–18.79	16.6–90.7

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

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

It is thus proposed that the rather poor reservoir quality generally characterising the sandstones of the GANT#1 core mainly results from compaction of a poorly sorted sediment containing ductile clasts combined with precipitation of minor amounts of diagenetic minerals during shallow burial reducing primary porosity (Kierkegaard 1998).

Although the reservoir properties of the sandstone intervals in the GANT#1 and GANE#1 wells are generally relatively poor, it is suggested that moderate to good properties may be found in certain intervals within the Maastrichtian–Paleocene succession. However, the reason for the locally enhanced reservoir properties in GANT#1 was not clarified by this study partly due to the lack of regional petrographical data.

Palynostratigraphic, lithological and petrophysical evaluation of the GRO#3 well

In 1996 grønArctic Energy Inc. drilled an exploration well (GRO#3) to a depth of 3 km (Fig. 1). The well penetrated Paleocene and Upper Cretaceous sandstones and mudstones but cores were not taken. The upper part of the well can be correlated with the GANE#1 well which is situated just 4 km west-north-west of GR0#3 (Kristensen & Dam 1997, app. 1).

The palynostratigraphy of the GRO#3 well has been described by Nøhr-Hansen (1997), who divided the uppermost 1485 m of the well into seven dinoflagellate cyst intervals (cf. Kristensen & Dam 1997, app. 1). Below 1485 m the sediments are thermally altered to such a degree that palynological dating is not possible. The dated succession has a ?Coniacian–Upper Selandian age. By comparing log patterns, lithology and palynostratigraphy of the well with outcrops in the Itilli valley the penetrated succession is provisionally divided into four units (Kristensen & Dam 1997, app. 1).

The lowermost unit is referred to as unnamed Upper Cretaceous sediments and is more than 2 km thick. The uppermost 500 m of this unit have a ?Coniacian to Late Campanian age (palynostratigraphic intervals VI and VII of Nøhr-Hansen 1997b); the lowermost 1500 m have not been palynostratigraphically dated. The unit consists of intervals dominated by mudstone, interbedded sandstone and mudstone, and sandstone which are cut by 14 igneous intrusions. The mudstone and the interbedded sandstone and mudstone intervals are homogeneous and up to 200 m thick. These sections show a very blocky log pattern and no overall coarsening-upward or fining-upward cycles are observed. They are interbedded with sharply based sandstone intervals that are from a few metres to more than 50 m thick and which commonly show an overall fining-upward trend. Based on field observations from the Itilli succession (cf. Dam & Sønderholm 1994a) it is suggested that this unit was deposited in a slope apron environment and that the sandstones were deposited in slope channels (Kristensen & Dam 1997).

The second unit, referred to as the Kangilia Formation is 241 m thick and has an Early to Late Maastrichtian age (Kristensen & Dam 1997, app. 1). It consists of three sharply based sandstone intervals, 38–83 m thick, separated by thin mudstone intervals. The log pattern is similar to that of the underlying unit and hence a slope apron environment with deposition of sandstone in slope channels is envisaged. Based on a comparison with exposures and additional well information (GANT#1) from northern Nuussuaq this unit is probably underlain by a regional unconformity.

The third interval, referred to as the Quikavsak Member, is 294 m thick and consists of an overall fining-upward, sandstone-dominated succession penetrated by several igneous intrusives. The unit has a Danian–Early Selandian age (Kristensen & Dam 1997, app. 1). This unit represents a major incised slope canyon formed during uplift of the basin in Paleocene times (cf. Dam *et al.* 1998). The unit can be correlated to the GANE#1 well where it is fully cored and comprises a thick succession of amalgamated, thickly-bedded coarse- to very coarse-grained sandstone beds, deposited from sand-rich turbulent flows.

The uppermost unit, referred to as unnamed Selandian sediments, is 120 m thick and consists of mudstone and interbedded mudstone and sandstone penetrated by a few thin igneous intrusives (Kristensen & Dam 1997, app. 1). The sediments are sharply overlain by volcanics. This unit can be correlated to the GANE#1 well. The sediments of the GANE#1 core reflect deposition in a marine slope environment. Depositional processes were dominated by low- and high-density turbidity currents, debris flow, slumps and fall-out from suspension. Deposition took place in slope feeder channels, small distributary feeder channels, and unstable interdistributary areas (Dam 1996a).

The sedimentary succession is overlain by 300 m of Paleocene volcanic rocks (Kristensen & Dam 1997, app. 1).

The petrophysical evaluation indicates that the GRO#3 well is characterised by low to fair porosities ranging from 5% to 15%; in general the porosity of the sandstones decreases slightly as a function of depth (Kristensen & Dam 1997). Eight sandstone intervals in the main hole were drill stem tested by grønArctic. Some of the intervals did not flow, some intervals flowed minor amounts of gas at very low rates, a reservoir performance that suggests that the sandstones tested are tight.

The sandstones of Quikavsak Member are characterised by low shale content and fair porosities (10–15%) and these sandstones are in particular considered to be potential reservoir rocks. This is reflected by deep mud invasion presumably related to the use of a relatively high mud weight (Kristensen & Dam 1997). According to a quantitative interpretation of the logs acquired in the well, these sandstones exhibit hydrocarbon saturations of up to 50% (Kristensen & Dam 1997). The saturation estimates are, however, subject to some uncertainty due to mud invasion, little knowledge of formation water composition and of the petrophysical properties of the shales, and a newly acquired reinterpretation of data suggests that saturations may be as high as 60 to 70%. However, more reliable estimates require further petrographic and petrophysical analysis. In addition to the dual laterolog (LLD-LLS), information on the flushed zone resistivity (R_{xo}) is needed to perform a reliable invasion correction, but no proper R_{xo}-log has been acquired in GRO#3. Unfortunately, the Quikavsak Member sandstones were not drill stem tested. The intermediate hole section, including the Quikavsak Member sandstones, was cased off prior to the drilling of the main hole.

The correlation with GANE#1 (Kristensen & Dam 1997, app. 2) suggests that GRO#3 is situated in an up-dip direction of the GANE#1 well on a structural high, and in this connection it is notable that hydrocarbons have been recorded in the same intervals in the two wells.

Conclusions

On the basis of geophysical surveys the main prospective area in the Nuussuaq Basin is presently constrained to a region stretching from north-western Disko across Vaigat and central Nuussuaq, east of the Itilli fault and somewhat further north into Uummannaq Fjord. This region is characterised by a thick sedimentary succession and large, rotated fault blocks which could provide structural traps. This area also includes the main surface indications of oil. Outcrops, subcrops and seismic facies indicate the presence of both source rocks, reservoir rocks and seals.

Oil seeps indicate the presence of 5 distinct oil types representing Upper Cretaceous and Paleocene sources. The only documented source rocks comprise Selandian turbidite mudstones (encountered in the uppermost part of the GRO#3 and GANE#1 wells) and Lower Campanian – Danian turbidite mudstones (found in the GRO#3 well).

Within the prospective area the potential reservoir units include fluvio-deltaic sandstones of the mid-Cretaceous Atane Formation, marine slope channel sandstones of the mid-Cretaceous–Paleocene Itilli succession/Kangilia Formation and marine canyon sandstones of the Paleocene Quikavsak Member.

Diagenesis studies suggest, however, that the most promising reservoir intervals within the turbiditic sandstones are restricted to sandstones of Late Maastrichtian–Paleocene age. These may show porosities higher than 10% and permeabilities ranging from 20mD to 90mD. The diagenesis studies show that the overall low porosities of the Campanian marine sandstones is mainly controlled by the content of ductile detrital grains, which includes mudstone clasts, plant debris, mica, and microcrystalline siderite aggregates. In general the sandstones can be classified as poorly sorted subarkoses; however, the Upper Maastrichtian–Paleocene sandstones seem to be better sorted and contain little, if any, detrital clay.

A palynostratigraphical, lithological and petrophysical evaluation of the 3000 m deep GRO#3 well indicates that it penetrates a ?Coniacian–Upper Selandian succession of interbedded marine sandstones and mudstones deposited in a slope apron environment. The Paleocene sandstones are characterised by low shale content and fair porosities (10–15%) and are in particular regarded to be potential reservoir rocks. According to a quantitative interpretation of the logs acquired in the well these sandstones exhibit hydrocarbon saturations of up to 50%. The saturation estimates are, however, subject to some uncertainty and a newly acquired reinterpretation of data suggests that saturations may be as high as 60 to 70%. However, more reliable estimates require further petrographic and petrophysical analysis.

The combined results from the geophysical surveys, the organic geochemical and diagenesis studies and from the evaluation of GRO#3 have profound implications for future petroleum exploration activities in the Nuussuaq Basin. The geophysical data indicate that large, rotated fault blocks providing possibilities of major structural traps are present in the western part of the basin. Adequate source rocks are documented in the succession both from wells and from surface oil seeps. Potential reservoir units occur throughout the sedimentary succession; especially the Upper Maastrichtian–Paleocene marine turbiditic sandstones may show good reservoir properties. Furthermore, the less consolidated parts of the fluvio-deltaic Cretaceous sandstones may also prove to be prospective reservoirs. The possible high content of hydrocarbons within the Paleocene sandstones in the GRO#3 well suggests that geological conditions may be favourable for hydrocarbon accumulations in the western part of the Nuussuaq Basin.

Recommendations

Based on the present study, the following recommendations for further scientific and exploration work are suggested.

- Onshore seismic surveys in the main prospective area on western Nuussuaq to delineate major structural elements more precisely.

- Drilling of a series of shallow stratigraphic wells in order to explore the 3–dimensional extent and internal variability of the slope channel reservoir units.

- Regional petrographical analysis of both the marine and non-marine Cretaceous–Paleocene successions in the Nuussuaq Basin in order to; a) resolve to what extent sedimentary facies and provenance influence reservoir properties, and b) to constrain petrophysical log-evaluation.

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