

Petroleum geological activities in West Greenland in 2000

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The summer of 2000 was exciting for everyone interested in the petroleum geology and exploration of West Greenland. The first offshore well in more than 20 years was drilled by the Statoil group in the Fylla licence area, and seismic acquisition activity offshore West Greenland was more intense than previous years with four new surveys being carried out (Fig. 1).

Expectations were high when drilling of the Qulleq-1 well was initiated in July 2000, not only with the licensees and the authorities, but also with the public. The well was classified as highly confidential, but nevertheless all information available was closely followed by the press, especially in Greenland and Denmark, but also internationally (see Ghexis 2000). Disappointment was equally high when the press release in September 2000 reported that the well was dry. Since that time much technical work has been carried out by Statoil and its consultants (Pegrum *et al.* 2001) and by the Geological Survey of Denmark and Greenland (GEUS), and a more balanced view of the positive and negative surprises from the well can now be presented.

When the licence was granted in December 1996, the Fylla licence area consisted of two sub-areas totalling 9487 km². Recently the Statoil group relinquished the eastern sub-area, which covers 2645 km², after having fulfilled their exploration obligations (Fig. 1). As a consequence, all data within the eastern sub-area are now 'open file' and available from GEUS. The relinquished eastern sub-area is included in the forthcoming licensing round, which has a planned closing date in early 2002.

Although the Qulleq-1 well did not discover hydrocarbons, it has produced new information important to the evaluation of the petroleum exploration potential of offshore West Greenland. With a licensing round in prospect and the several seismic surveys carried out in the summer of 2000 providing many new and interesting exploration targets, Greenland is prepared for continued exploration on a sound geological background,

Table 1. Well data for Qulleq-1 (6354/4-1)

Operator:	Statoil A/S
Drill ship:	West Navion
Well name:	6354/4-1 (Qulleq-1)
Co-ordinates:	63°48'48.03" N, 54°27'06.61" W
UTM co-ordinates:	E 625442, N 7078718; Zone 21; central meridian 57°W
Well classification:	Wildcat
Rotary table:	36 m above sea level
Well spud:	10 July 2000
Well termination:	4 September 2000
Total measured depth:	2973 m RT
Water depth:	1152 m
Core:	No conventional core taken
Sidewall core:	150 shots, 120 recoveries, 5 misfired and 25 lost
Logs:	Wireline: gamma ray, resistivity, density, neutron, sonic, caliper and SP MWD while reaming from 1920 m–TD: gamma ray, sonic, density, neutron, resistivity and acoustic caliper
Formation drilled:	Quaternary, Palaeogene and Campanian mudstone; Santonian sandstone
Hydrocarbons:	No hydrocarbons
Test:	MDT: 11 pressure points were tested and 1 fluid sample collected
Status:	Plugged and abandoned
Prospect type:	Upper Cretaceous reservoir with cross-cutting reflection in a major rotated fault block structure

despite the temporary setback from the disappointing outcome of Qulleq-1.

Drilling of the Qulleq-1 well and release of data

The Qulleq-1 well was drilled by the Statoil group as part of their commitments in the eastern sub-area of the Fylla licence. The official well designation according to the existing block system is 6354/4-1, but the name Qulleq-1, which is derived from the Greenlandic word

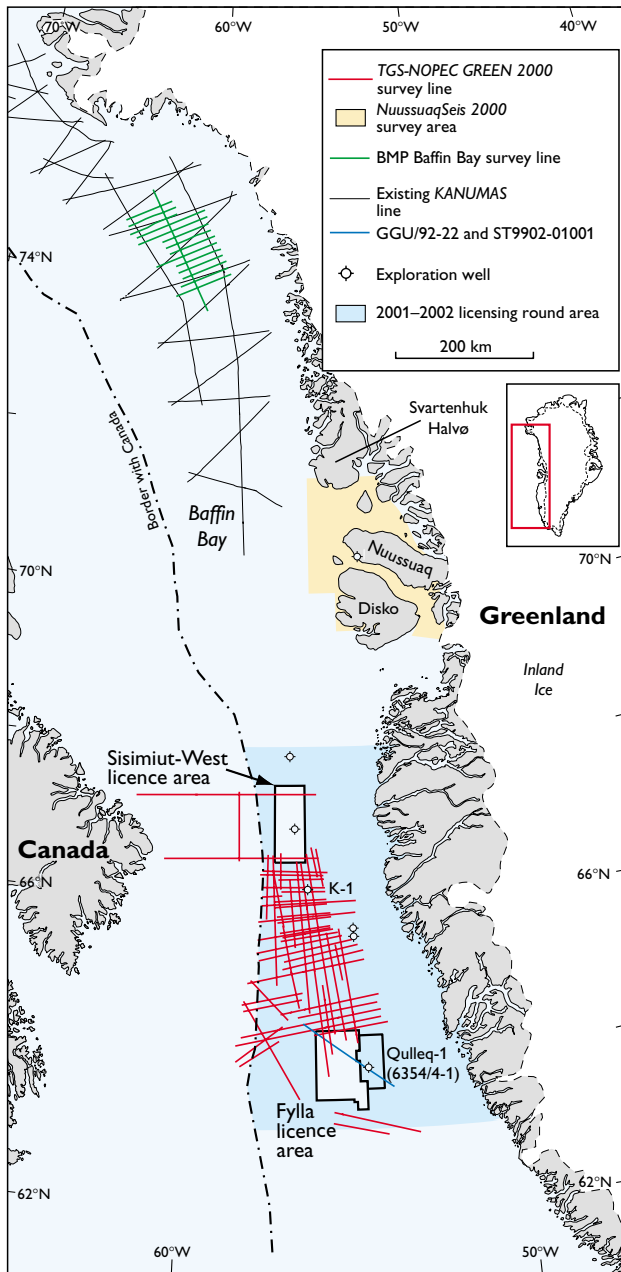


Fig. 1. Map of West and North-West Greenland showing seismic lines acquired during summer of 2000, licence areas and area covered by 2001–2002 licensing round. **K-1**: Kangâmiut-1 well.

for a train-oil lamp, has also been used by both Statoil and the authorities. The well was drilled with the newly built drill ship *West Navion* (Fig. 2). It was spudded in 1152 m water depth on 10 July and reached total depth (TD) at 2973 m below rotary table (RT) before it was plugged and abandoned in early September (see well data in Table 1).

Although the density of icebergs in the drilling region was higher than expected, downtime due to icebergs



Fig. 2. *West Navion* drilling off West Greenland in 2000. Photo courtesy of Smedvig asa.

in the vicinity of the drill ship was only 33 hours (Ghexis 2000). On the other hand, there was approximately 4 weeks of downtime during the drilling period due to technical problems with the blow out preventer (BOP) and wellhead.

The sampling programme during drilling has given some limitations in interpretation of the results of the well, as no cores were taken. Furthermore, cuttings are not available from the uppermost ~ 600 m of the hole, because it was drilled riserless; only minor amounts of material were collected from this interval from the seabed using a remote operated vehicle (ROV). However, an extensive sidewall-core programme has been very important for biostratigraphic studies and also for interpretation of lithology. A total of 120 of 150 sidewall cores were recovered. Due to serious hole problems in the deeper part of the well, logging of the interval below ~ 2205 m could only be carried out during a wiper trip using 'Measuring While Drilling' (MWD) tools.

Some of the main results from the well are reported briefly below. Biostratigraphical, organic geochemical and petrographical details may be found in consultancy reports produced for the Statoil group (Bojesen-Koefoed *et al.* 2000; Nøhr-Hansen *et al.* 2000; Preuss & Dalhoff 2001; Preuss *et al.* 2001). All depths in the text and figures are in metres below rotary table (RT).

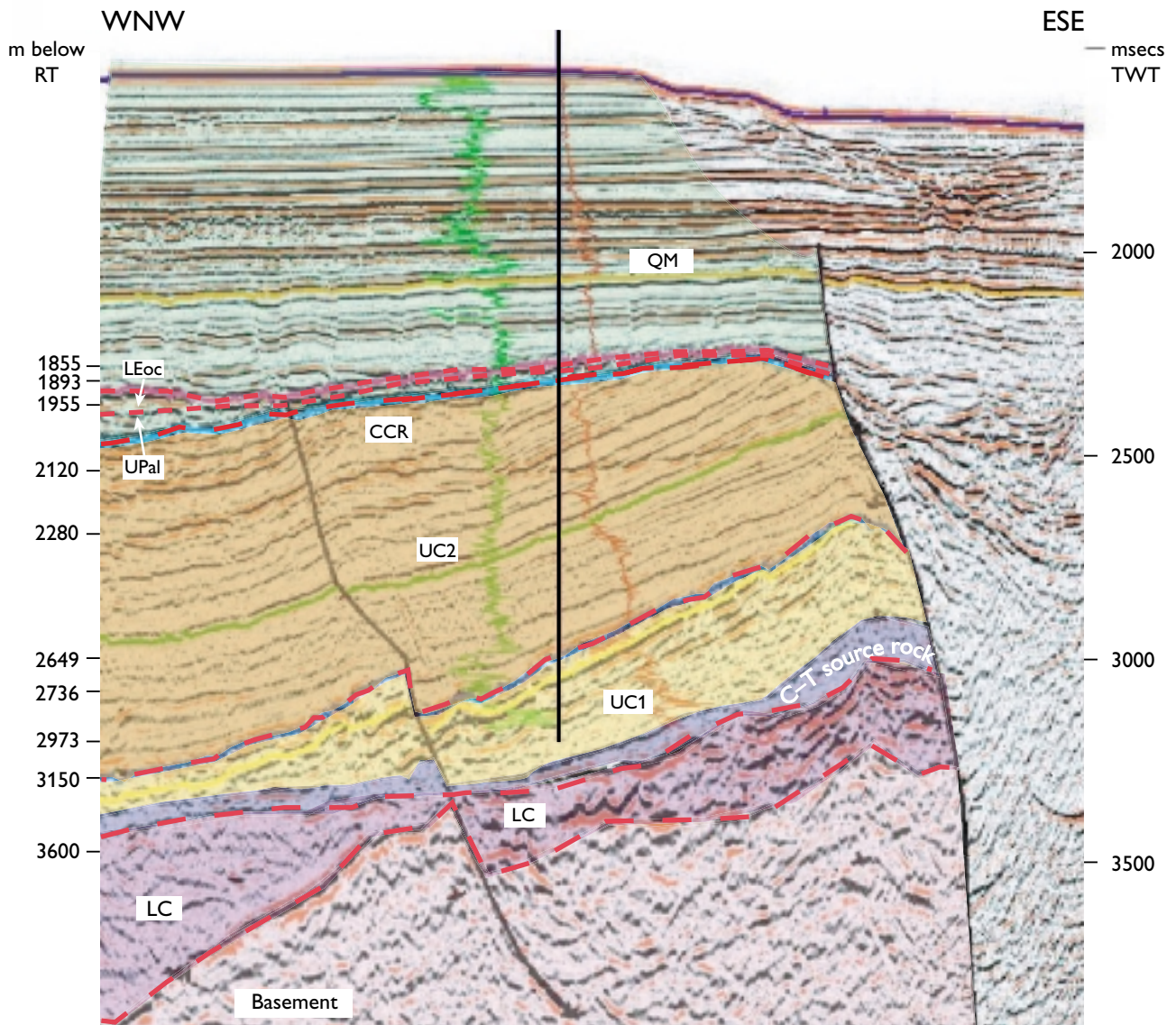


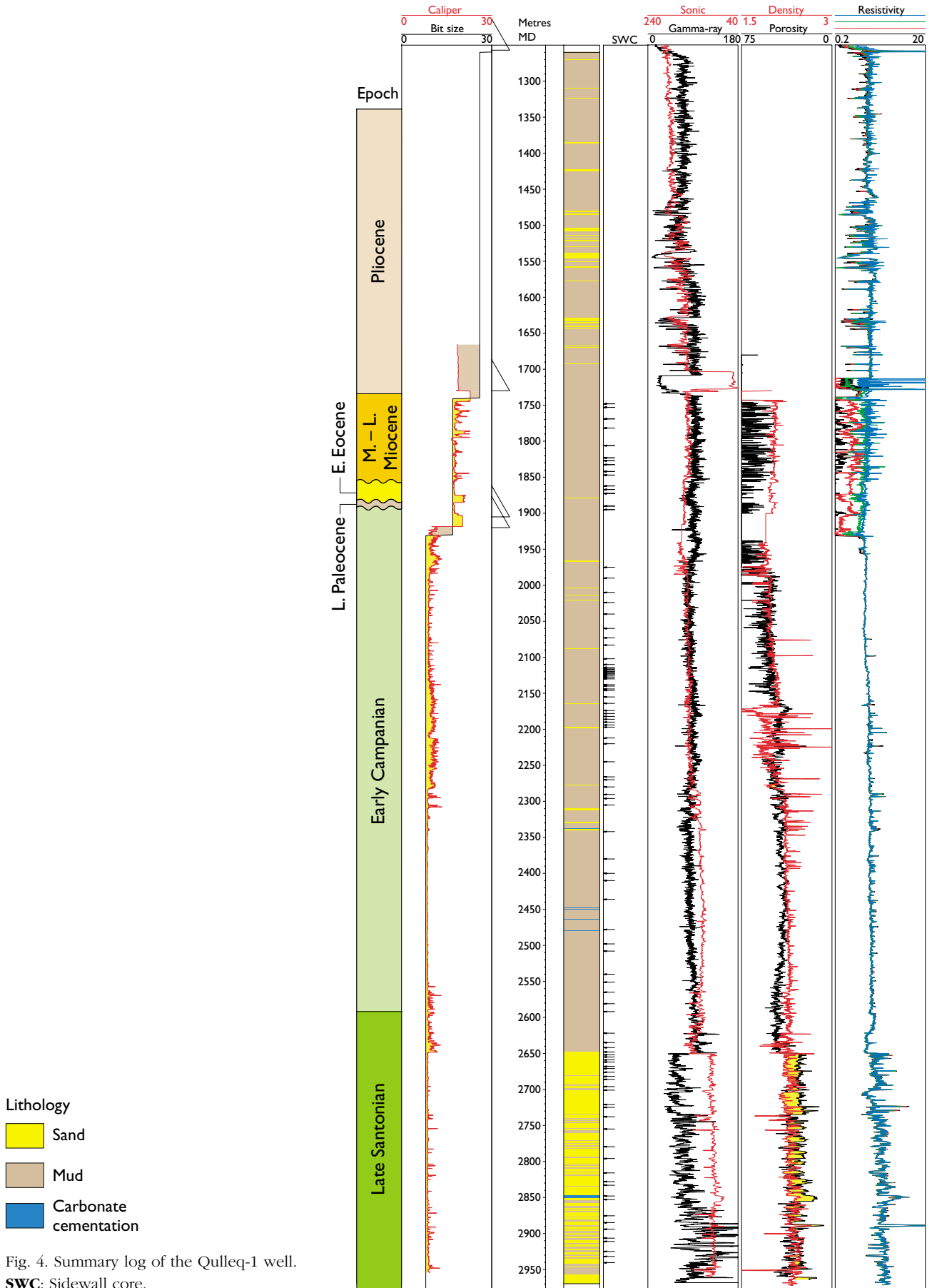
Fig. 3. Seismic line ST9902-01001 through the Qulleq-1 (6354/4-1) well. See Fig. 1 for position. The gamma-ray log is shown in **green** to the left of the well and the acoustic impedance log is shown in **red** to the right. Note that there is no significant change in acoustic impedance at the cross-cutting reflection (CCR) at 2537 msec TWT. **LC**: ?Lower Cretaceous; **UC**: Upper Cretaceous; **UPal**: Upper Paleocene; **LEoc**: Lower Eocene; **QM**: Quaternary – Middle Miocene. **TWT**: Seismic two-way-time.

Exploration targets

The main target of the Qulleq-1 well was the prominent cross-cutting reflection (CCR) which can be seen on the seismic data at around 2550 msec two-way travel time (TWT) corresponding to a depth of c. 2100 m (Fig. 3). Extensive analysis of all data available prior to drilling (including amplitude versus offset (AVO) analysis of the seismic data) suggested that this reflection represented a gas-liquid contact in a compartmentalised turbidite sandstone succession (e.g. Bate *et al.* 1995; Aram 1999; Isaacson & Neff 1999). The well,

however, encountered only mudstones in this interval and no gas or oil. At present, the nature of the CCR is not fully understood, but X-ray diffraction analysis of sidewall cores by Statoil suggests that it may be related to a phase-change transition from opal-CT mineralisation to quartz mineralisation.

Prior to drilling, TD was planned to 2850 m, just below a strong, regionally developed seismic reflection (~ 3100 msec, Fig. 3), which was interpreted to be a source rock interval of possible Cenomanian– Turonian age. This reflection turned out to be the contact between Lower Campanian mudstones above and Upper



Santonian sandstones of reservoir quality below. As a result of the unexpected age and lithology of the sediments in this part of the section, and the lack of hydrocarbons at the CCR, it was decided to deepen the well to a maximum of 3000 metres. However, due to technical problems it was not operationally feasible to go deeper than the final TD of 2973 m.

The possibility of reaching deeper targets in the inferred Lower Cretaceous succession, or to penetrate the full stratigraphic succession to basement, was not considered by the Statoil group (Pegrum *et al.* 2001). At the actual drilling position, however, continued drilling, if undertaken, would penetrate deeper reservoir targets below structural closure and probably below spillpoint.

Stratigraphic units

With the new results from the Qulleq-1 well, it is now possible to interpret the seismic data from the region in more detail. Four major stratigraphic units including basement, a syn-rift succession seen in half-graben structures, a tilted fault-block succession and a draping, more or less flat-lying succession can be identified on the seismic data. However, only the upper two of these were penetrated by the well (Figs 3, 4).

The drilling demonstrated that the youngest unit draping the large, tilted fault-blocks of the Fylla structural complex consists of mid-Upper Paleocene to Quaternary mudstone-dominated, fully marine deposits (1152–1893 m). From outcrop and older well data, as well as from regional seismic data, two hiatuses spanning the interval across the Paleocene–Eocene boundary and the uppermost Middle Miocene to uppermost Early Eocene were expected, and their presence was confirmed at ~ 1885 m and ~ 1860 m, respectively. Prior to drilling, Statoil's well programme had identified several potential drilling risks in this unit including the presence of large boulders (dropstones) in the Pliocene–Quaternary succession, shallow gas in a possible sandstone interval (seen as a high amplitude reflection at ~ 1900 msec on the seismic data), and possibly thin volcanic ash layers. Due to expected relatively low temperatures and the large water depth, the possibility of gas hydrates was considered a major risk while drilling and during any well control events. In the event, none of these risk elements were encountered during drilling. There was no evidence of shallow gas or gas hydrates, boulders were avoided and the age interval with possible volcanic rocks is missing due to a major hiatus.

Within the tilted fault-block succession two units differing in lithological and seismic character can be identified (Figs 3, 4).

The upper unit (1893–2649 m; 2318–3007 msec) is characterised by good seismic reflectivity and lateral continuity although it is somewhat transparent (UC2 on Fig. 3). When drilled it was found to consist of fully marine mudstones of Early Campanian age (Fig. 4). The unconformity between the Palaeogene and the Upper Cretaceous penetrated by the well spans the Early Campanian to mid-Late Paleocene, representing about 12–15 million years (Nøhr-Hansen *et al.* 2000).

The lower unit (2650–2973 m; 3007 to ~ 3300 msec) is characterised by good reflectivity and lateral continuity of units (UC1 on Fig. 3). The upper part of this unit comprises a fully marine, sandstone-dominated succession of Late Santonian age. The first possible Upper Santonian strata are found at 2635 m and, although the seismic data suggest an unconformity between the sandstone-dominated unit and the overlying mudstones, there is no evidence of a hiatus or condensed section (Fig. 4; Nøhr-Hansen *et al.* 2000).

The syn-rift succession (~ 3300 to ~ 3600 msec) was not reached by the well but may be seen on the seismic data as a distinct change in seismic character (Fig. 3). The boundary with the overlying unit is unconformable and could represent a regionally mappable contact between Lower Cretaceous syn-rift sediments (fluvial or shallow marine) below and fully marine mid-Cretaceous/Upper Cretaceous sediments including a possible Cenomanian–Turonian source rock interval above.

Basement is difficult to delineate on the seismic data, but may be seen at around 3500 msec at the well position in Fig. 3. The crystalline basement may, however, be covered by both Ordovician limestones and Jurassic sediments, since Jurassic spores have been found in side-wall cores in the well (Nøhr-Hansen *et al.* 2000).

Santonian reservoir sandstone

Qulleq-1 encountered ~ 90 metres of reservoir-quality sand below which is a sandstone-dominated unit down to TD also showing reservoir potential (Fig. 4). The gamma-log signature suggests that the penetrated Upper Santonian sandstone succession could be divided into three sub-units (Fig. 5). The sandstones are, however, both immature (with abundant feldspar, mica, pyroxene and rock fragments) and glauconitic. It is therefore not possible to relate the gamma-ray curve directly to sandstone/shale ratio. The main (upper) reservoir sandstone appears to exist within much or all of the struc-

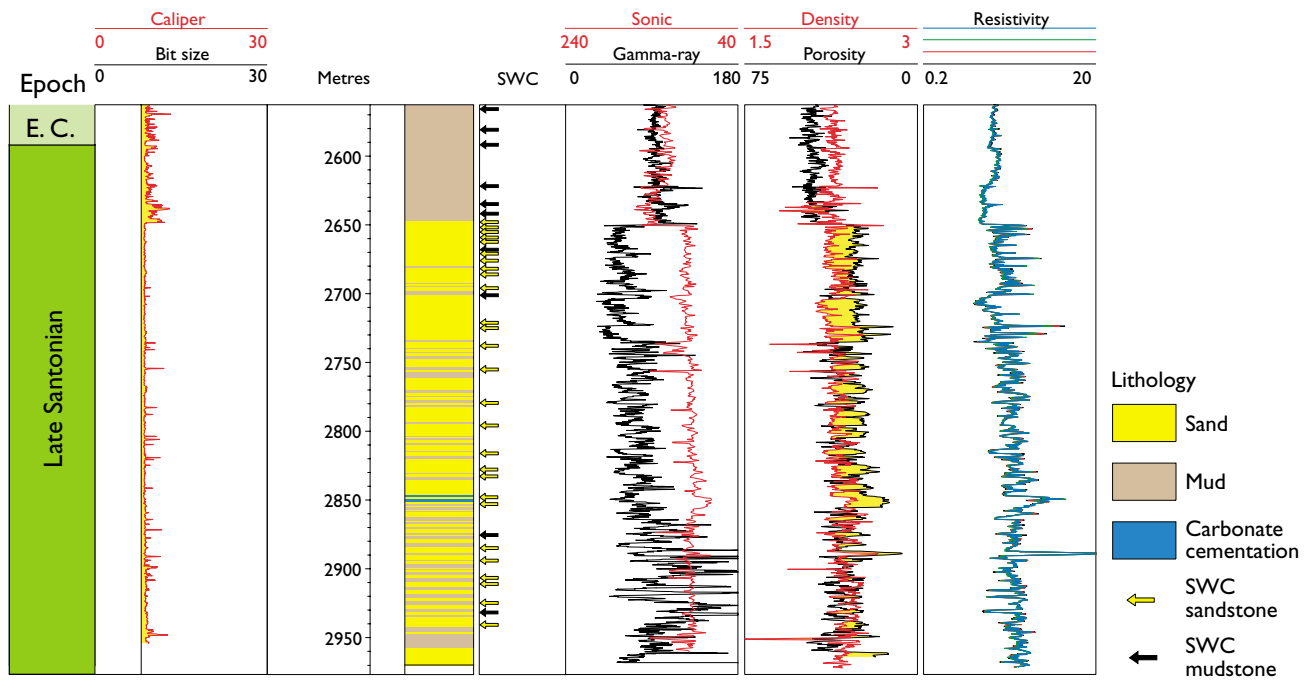


Fig. 5. Detailed log of the Santonian sandstone reservoir unit in the Qulleq-1 well. **SWC**: Sidewall core. **E.C.** Early Campanian.

ture shown in Fig. 8, but the character of the reflections changes from place to place indicating some changes in lithology or petrophysical properties. Unfortunately, the thickness of the best reservoir interval is close to seismic resolution, so it is not a simple task to relate the changes in seismic character to changes in lithology and reservoir properties.

Organic geochemistry and thermal maturity

Organic geochemical analyses of samples from the Qulleq-1 well were hampered by pervasive contamination by polyalkyleneglycol (PAG) – a drilling mud additive which was used in very high concentrations because of the risk of gas hydrates. Attempts to remove the contaminant failed, and Rock-Eval/TOC screening data from the well are therefore largely useless (see details in Bojesen-Koefoed *et al.* 2000). Generally, total organic carbon (TOC) values are below 0.5 wt% in the Palaeogene–Neogene mudstone unit, whereas most of the Lower Campanian marine mudstones show values between 1 and 2 wt%. The data show that no prolific petroleum source rocks are present within the drilled succession. Over the interval 2739–2811 m, a number of mudstone samples show relatively high TOC values (3–7 wt%). Mathematical curve-fitting carried out on original Rock-Eval pyrograms allowed elimination of the effects of PAG contamination, and showed that, despite high organic matter contents, these deposits possess

only marginal source rock potential with corrected hydrogen indices (HI) < 120. Visual kerogen analyses confirm these results, showing the kerogen to consist predominantly of coaly and non-fluorescent amorphous organic matter.

Analysis of sandstones from sidewall cores was carried out in an attempt to detect traces of migrated petroleum, but the results showed only PAG and various other contaminants. No traces of migrated hydrocarbons were detected.

Since optical analyses were unaffected by PAG-contamination, a well-constrained maturity trend could be established (Fig. 6). Vitrinite reflectance (R_0) measurements show the succession to be immature with respect to petroleum generation. The top of the ‘oil window’ is projected to be at about 3160 m, corresponding to c. 200 m below TD of the well. No significant changes of vitrinite reflectance are observed across biostratigraphic hiatuses. Based on the projected vitrinite reflectance level at the seabed, it may be concluded that the succession is near its maximum depth of burial.

Basin modelling

With new knowledge on the thermal maturity and temperature gradients in Qulleq-1, together with a reinterpretation of the seismic data based on new lithological and biostratigraphic information, the 2D basin modelling of the Fylla area has been revised.

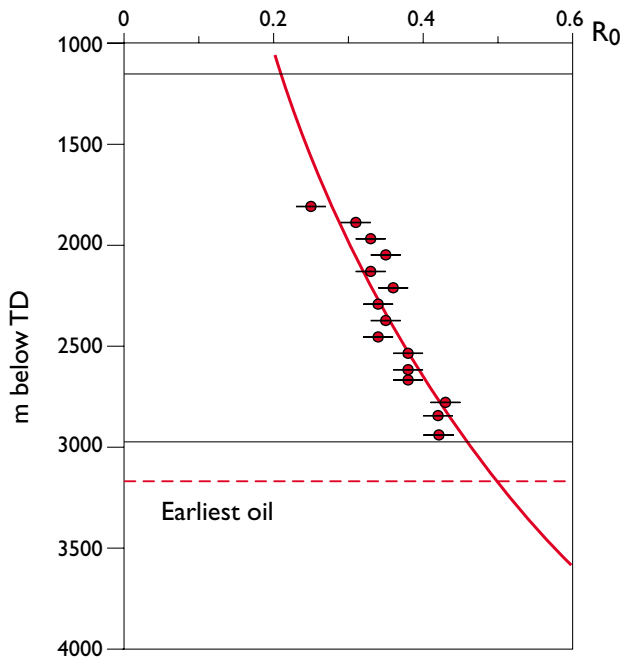


Fig. 6. Vitrinite reflectance versus depth in Qulleq-1.

The model clearly demonstrates that the sedimentary succession penetrated by Qulleq-1, as well as most of the succession underlying TD, is immature and that the assumed Cenomanian–Turonian source rock is immature in the vicinity of Qulleq-1 (Fig. 7). It is, however, evident from the modelling that this interval is situated in the main oil window in the two fault-blocks immediately east of Qulleq-1 (Fig. 7). The Cenomanian–Turonian is also inferred to be mature in the westernmost part of the Fylla licence area, although the lack of a seismic tie across the main fault zone makes it difficult to predict the position in detail. This suggests that the seismic line GGU/92-22 intersects three major kitchens for hydrocarbon generation, results which have very important implications for prospectivity. If the modelling data from line GGU/92-22 are used to predict the position of the oil generation zones throughout the Fylla area, and if there is a source rock in these localities, a number of other kitchens and migration pathways can be mapped (Fig. 8).

Seismic reinterpretation of the cross-cutting reflection

The results of the Qulleq-1 well show that the forecast Upper Cretaceous reservoir consists entirely of mudstone, and that the cross-cutting reflection (CCR) may be related to the phase transition from opal-CT to quartz. The acoustic impedance log shows no significant change in

acoustic impedance at the depth of the CCR (Fig. 3), which raises the question about the origin of the prominent reflection. Isaacson & Neff (1999, fig. 13) show an increase of amplitude with offset for the CCR, and a decrease in amplitude with offset for the top Cretaceous reflection. These observations could indicate that there is significant seismic anisotropy within the opal-CT section. Such anisotropy could result in significantly different *horizontal* acoustic impedances in the opal-CT and quartz sections and little or no reflection of near vertical seismic energy, but significant reflection of far-offset rays. A stacked section which shows the summed contribution of both near- and far-offset energy, consequently shows the CCR from the far-offset traces only.

Summary of results

The drilling of the Qulleq-1 well, not unexpectedly, gave some surprises. Organic geochemistry, biostratigraphy, log interpretation and seismic reinterpretation have provided new information of importance for assessment of the petroleum potential of offshore West Greenland.

1. Seismic velocities in the Qulleq-1 well are distinctly lower than in all other wells in West Greenland.
2. In contrast to all the previous wells (Rolle 1985) there is surprisingly little sand in the Neogene succession.
3. Several of the drilling risks considered before drilling are now known not to apply to this part of the basin.
4. The major hiatuses in and bounding the Palaeogene were expected and their ages confirmed.
5. The age and lithology of the seismic units within the tilted fault-blocks were not as expected. The upper units are somewhat older than expected, and consist of mudstone where substantial amounts of sand were expected (Bate *et al.* 1995; Aram 1999; Isaacson & Neff 1999). The deeper units are significantly younger (Santonian instead of Aptian/Albian) and reservoir-quality sand was found where it was hoped to encounter Cenomanian–Turonian source rock. This information has both negative and positive implications for the exploration possibilities.
6. The CCR is not related to a gas–liquid contact. The ‘flat spot play’ in the Fylla licence area seems to be dead.
7. The well-penetrated sediments are only immature for oil generation, and the main oil window (peak generation) is deeper than TD.

Fig. 7. 2D basin modelling of seismic line GGU/92-22 using the IES PetroMod® 2D modelling software. The model describes all important basin processes and data as a function of time. The figure shows the subdivision used in Qulleq-1 with modelled thermal maturity on a modelled depth-converted seismic line. Note the position of the Santonian sand unit and the possible Cenomanian–Turonian source rock interval in the kitchens east and west of Qulleq-1. See Fig. 1 for position of seismic line.

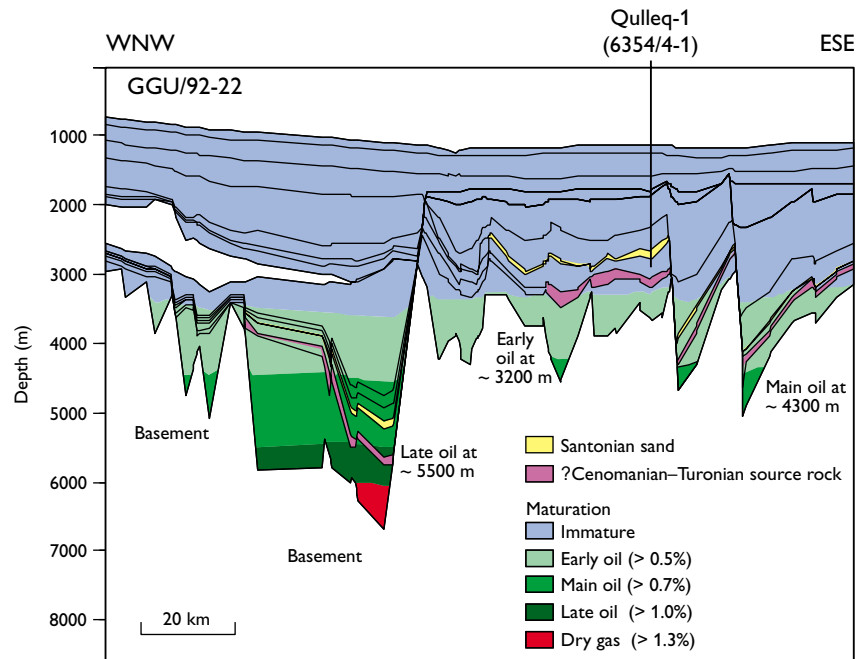
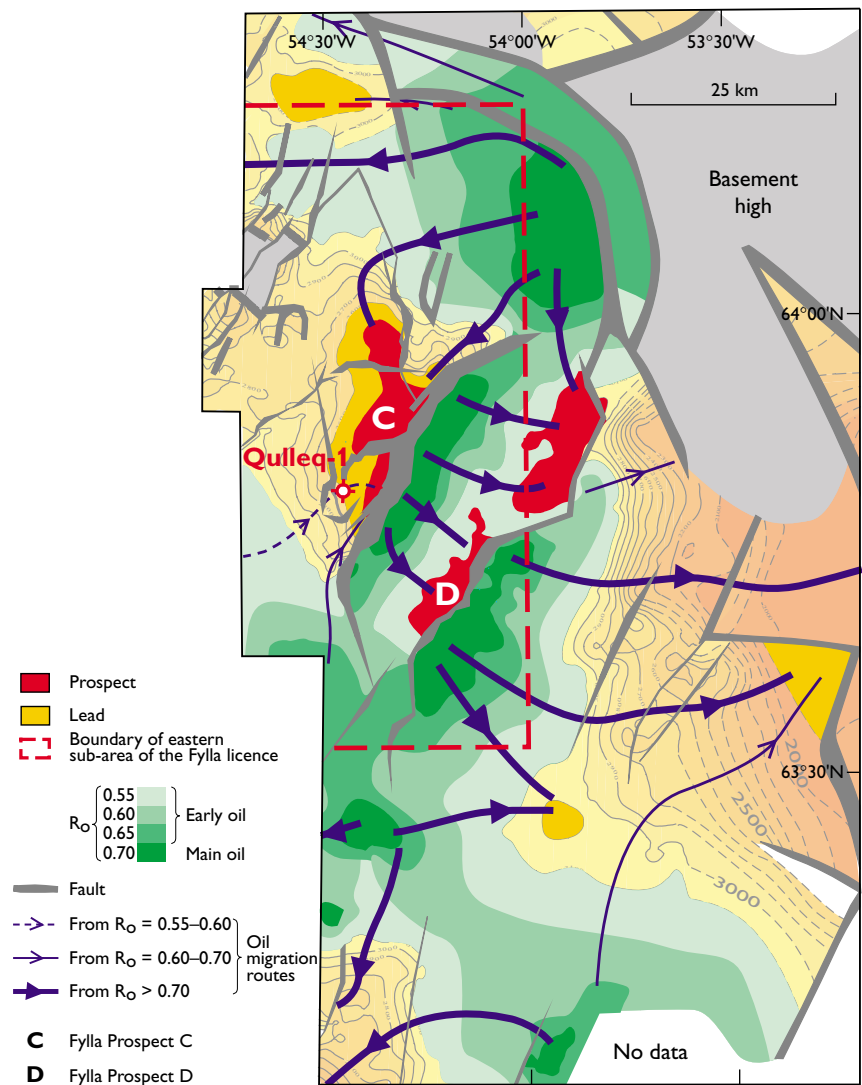


Fig. 8. Map showing depths in metres below sea level to the top of the Santonian sandy interval penetrated by Qulleq-1 at 2749 metres below rotary table. The crest of the structure is more than 800 metres shallower than the depth at which the well penetrated the horizon. Overlain colours indicate where a potential Cenomanian–Turonian source rock may be mature. Migration routes of oil from kitchen areas to leads and prospects are indicated. **Grey areas** represent faults.



8. Thermal maturity data show a simple trend and are in accordance with measured temperatures. This is not a surprise and makes exploration simpler.
9. The Qulleq-1 well was not drilled deeply enough, neither stratigraphically nor in absolute depth, considering the frontier nature of the Fylla area. Prospective successions of both presumed Early and Late Cretaceous age were left untouched below TD.
10. The Santonian reservoir sandstone that was found was penetrated more than 800 m below the crest of the prospect, and significant up-dip potential on the structure remains untested.

Implications for prospectivity

The results from the Qulleq-1 well have significant implications for the evaluation of the prospectivity of the region. For many years the main risk in assessing the potential of offshore West Greenland has been the question of whether or not oil-prone source rocks are present (see first discussion in Chalmers *et al.* 1993). This risk was considerably reduced with the finds of widespread oil seeps onshore in the Disko–Nuussuaq region (see Christiansen *et al.* 1994; Bojesen-Koefoed *et al.* 1999). Although the results of Qulleq-1 were not as hoped, they have neither increased nor decreased this risk, since the well did not reach the postulated Cenomanian–Turonian succession which is considered to be the most likely oil-prone source rock interval in the region.

The nature of the CCR is unrelated to hydrocarbon charge. The lack of high gas readings during drilling, and the lack of petroleum traces in cuttings and sidewall cores may be arguments for a higher risk of especially the presence of a source rock for gas. However, the well drilled mainly through immature mudstones, and the only potential reservoir sandstones were penetrated 700–800 m below the crest and close to spill-point of the structure.

The thermal maturity data and basin modelling suggest that a possible Cenomanian–Turonian oil-prone source rock would be mature in kitchens in the deeper synclines of the Fylla area fault-blocks, and that there are simple migration pathways into several large prospects with four-way dip closure; however, the well was on none of them (Fig. 8). One significant reservoir interval in the Upper Santonian has been demonstrated, and other reservoir sandstones may be present below the unconformity that is seen on the seismic data some hundred metres below TD of the Qulleq-1 well. The thick Campanian and Palaeogene–Neogene mudstone successions form an excellent seal to these prospects.

Seismic acquisition during summer 2000 – the Canadian connection

In the summer of 2000 three seismic vessels operated in the waters off West and North-West Greenland. The seismic company TGS-NOPEC extended their 1999 acquisition of non-exclusive seismic data in the area designated for the licensing round in 2001 (Fig. 1). The seismic survey vessel *Zephyr* acquired more than 6300 km of seismic data, mainly in the region between the Sisimiut-West and Fylla licence areas. In particular, the data coverage around the Kangâmiut-1 well (the Kangâmiut Ridge area) was improved considerably (Fig. 1). In order to link the Canadian and Greenland basins, TGS-NOPEC acquired three tie lines in Canadian waters. The TGS-NOPEC seismic data base off West Greenland now comprises more than 9000 km of high-quality data.

The Danish fishery inspection vessel *Thetis*, with seismic equipment and operated by Nunaoil, acquired proprietary seismic data within the Sisimiut-West licence area for the Phillips group (about 1200 km). The Bureau of Minerals and Petroleum (BMP), Nuuk, Greenland, funded a seismic survey in the Baffin Bay area of North-West Greenland. The survey was designed as infill to the existing regional KANUMAS survey in order to achieve a denser seismic coverage of leads observed on the KANUMAS lines. A total of 1340 km were acquired (Fig. 1).

GEUS used the Danish research vessel *Dana* to acquire high-resolution seismic data in the waters around Nuussuaq. This programme (*NuussuaqSeis 2000*) was undertaken in co-operation with Aarhus University, Denmark, and was funded by the Danish Energy Research Programme and BMP. This project aims to improve understanding of the structure of the shallow part of the Nuussuaq Basin. The new data will also have direct implications for assessing the hydrocarbon potential of the onshore areas. Due to excellent weather and favourable ice conditions, more than 2700 km of data were acquired in only 18 days (see Marcussen *et al.* 2001, this volume).

Onshore field work and other activities

For the first time in more than 10 years there was no petroleum-related onshore field work in the Disko–Nuussuaq–Svartenhuk Halvø region in 2000. Activities were restricted to a field trip organised by TGS-NOPEC with GEUS providing guidance in the field.

The extensive field programme that GEUS and collaborating partners have carried out throughout the

1990s has reached a temporary conclusion. Many of the results from this work are important for the evaluation of the exploration potential of the Nuussuaq Basin itself and also for the offshore areas. Several important studies have been published in 2000, including the structures of Svartenhuk Halvø (Larsen & Pulvertaft 2000), evidence of an Early Campanian rift-phase on Nuussuaq (Dam *et al.* 2000), specific compounds in seeping oils (Nytoft *et al.* 2000), a possible play showing seismic anomalies west of Disko (Skaarup *et al.* 2000) and documentation of major Neogene uplift in West Greenland (Chalmers 2000). Many other studies on basin history, sedimentological and structural models, lithostratigraphy, organic geochemistry of northern seeps etc. are in progress.

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