Petroleum geological activities onshore West Greenland in 1997

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The 1997 summer season saw continued petroleum geological activities in the Disko–Nuussuaq–Svartenhuk Halvø area, onshore West Greenland. These activities mainly took the form of a geological field project led by the Geological Survey of Denmark and Greenland (GEUS), whereas the continued exploration by grønArctic Energy Inc. (grønArctic) in the third year of their licence was kept at a very low level without field work, geophysical surveys or drilling. Furthermore an airborne geophysical survey, Aeromag 1997, covering a large part of the Disko Bugt area, was carried out in the early summer of 1997 with GEUS as project manager (Stemp 1997; Stemp & Thorning 1998, this volume).

Field work

The aim of the field work in 1997 was mainly to follow-up previous studies on Disko and Nuussuaq. In particular, this involved further search for, and sampling of, seepage and oil staining, not only on Disko and Nuussuaq, but also farther to the north on Ubekendt Ejland and Svartenhuk Halvø (Fig. 1). Sedimentological studies concentrating on general depositional models of the Upper Cretaceous and Paleocene successions were carried out on Disko and Nuussuaq. The structural studies of the western part of Nuussuaq were continued and a new study of the regional zeolite zonation of the volcanic succession on Disko and western Nuussuaq was initiated.

Seep studies

Encouraged by the many new oil seeps discovered during the 1996 field work and the subsequent organic geochemical results that have demonstrated at least five distinct oil types (Christiansen *et al.* 1997; Bojesen-Koefoed *et al.* in press), 'oil hunting' continued in 1997. Localities were selected on the basis of combinations of volcanic stratigraphy, structural position, lithology, porosity, and secondary structures in the volcanic rocks (Christiansen *et al.* 1997; Bojesen-Koefoed *et al.* in press); combining visual characteristics with the presence of a petroliferous odour was used successfully to locate new seeps on Nuussuaq as well as in areas farther to the north.

Many new localities were found and sampled in the vicinity of previously recorded seeps, especially in the area between the well sites GRO#3, GANE#1 and Sikillingi (Fig. 1). Much denser sampling was carried out in order to map the distribution of different oil types, and particularly in order to study the importance of the mixing of different oil types during migration, trapping and leakage. In two areas in particular, viz. Marraat and Sikillingi, major reservoir-like accumulations of almost non-degraded oil occur at or near to the surface plugging all available porosity in the volcanic rocks. Conservative calculations (see details in Bojesen-Koefoed *et al.* in press) suggest in-place oil volumes of several hundred millions of barrels and thereby indicate that the source rock(s) must have had a considerable generative potential, possibly sufficient to fill giant structures elsewhere or deeper in the basin.

New seep localities were also found in the north-western part of Disko and also in several places on Hareøen (Fig. 1). It is remarkable that pervasive oil staining has been recorded for the first time from outcropping sediments in West Greenland. Oil stained sediments have previously only been described from the cores of GANE#1 and GANK#1 (Christiansen *et al.* 1996) while one example of strongly altered bitumen on a sandstone surface was noted on Qeqertarssuaq by Henderson (1969). The documentation of relatively pervasive oil staining (moderately biodegraded) at Asuk on northern Disko (Fig. 3) looks promising for more discoveries in the future and for predicting a widely distributed oil-prone source rock in the non-marine Atane Formation of Cretaceous age.

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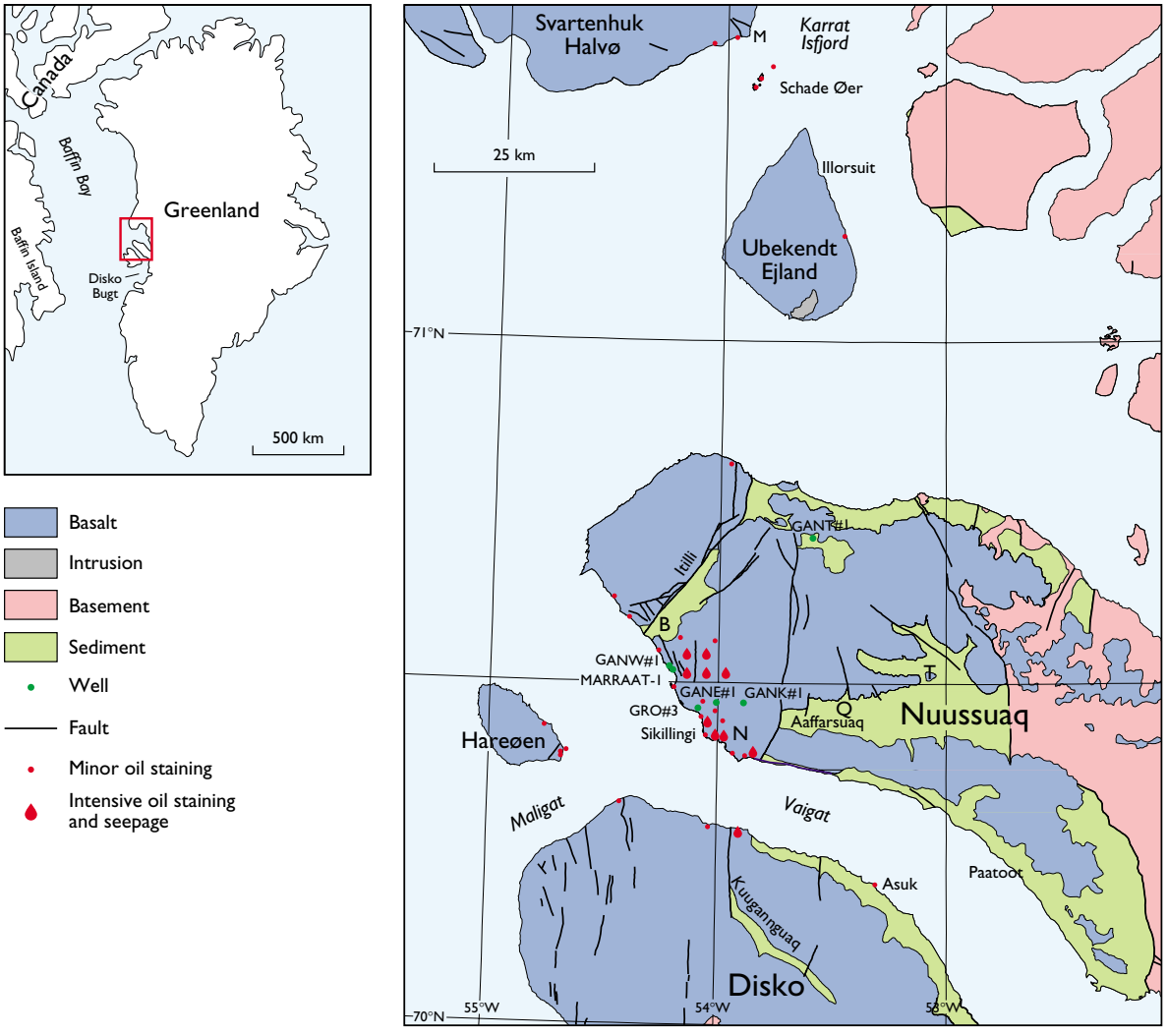

Fig. 1. Simplified geological map of the Disko–Nuussuaq–Svartenhuk Halvø area showing the position of wells and boreholes, and distribution of localities with seepage and staining of oil found in the period 1992–97. B: Bartschiakløft, M: Maniiseqqut, N: Nuusap Sanningasua, Q: Qilakitsoq, T: Tunoqqu. Based on published Survey maps.

Systematic search for oil staining was carried out for the first time within the Tertiary volcanic rocks to the north of Nuussuaq and led to several significant finds documenting the presence of oil over a distance of more than 150 km from Disko to Svartenhuk Halvø. The south-east coast of Ubekendt Ejland proved to be barren, probably due to metamorphism caused by heating from intrusions, but a systematic investigation along the east coast of the island led to location of a significant oil staining at a dyke contact about 12 km to the south of Illorsuit (Fig. 2), whereas most of the other tested localities were barren. On the small islands and skerries of Qeqertat (Schade Øer) in Karrat Isfjord weak but significant oil staining was found in hyaloclastite and lava belonging to the lower part of the volcanic succession. Further to the north around Maniiseqqut on the south coast of Svartenhuk Halvø a zone of intense oil impregnation was found within hyaloclastite cut by a major dyke. These rocks form the lowermost volcanic lithologies on Svartenhuk Halvø. A systematic search of the south coast of Svartenhuk Halvø over a distance of 35 km towards the west revealed only two localities with weak oil stains, both in carbonate veins along dykes cutting the lower part of the volcanic succession.

Fig. 2. Prominent N–S trending (190°/65° E) dyke from the eastern part of Ubekendt Ejland. Oil impregnation is common at the contact between volcanic rocks and the dyke. Person for scale.

Sedimentological investigations

A recently completed reservoir study of the most prospective area on Nuussuaq concludes that potential reservoir units include fluvio-deltaic sandstones of the Cretaceous Atane Formation, mid-Cretaceous–Paleocene marine slope channel sandstones and marine canyon sandstones equivalent to the incised valley fill sandstones of the Paleocene Quikavsak Member (Sønderholm & Dam 1998).

During the 1997 field season a number of outcrop studies were carried out in order to follow-up on the reservoir study and on previous year's field work on these stratigraphic units. The Atane Formation was studied on southern and central Nuussuaq, the Cretaceous–Paleocene slope succession was studied in the Aaffarsuaq valley, central Nuussuaq and the Paleocene unconformity and the incised valley sandstones were studied on northern Disko and on the south coast of Nuussuaq.

The Atane Formation is interpreted as an Upper Cretaceous succession of deltaic deposits characterised by accumulation of organic matter in non-marine environments. A major part of the 1997 field work aimed at a lateral correlation of measured sections. Lateral facies variations were noted in many of the depositional units suggesting that potential reservoirs are heterogeneous. The field work will be continued with the purpose of interpreting sediment transport directions, facies architecture and changes in delta palaeogeography, and establishing a depositional model for the Atane Formation. A depositional model may form the basis for the prediction of good reservoirs within the Atane Formation. The importance of the Atane Formation as a potential reservoir unit is stressed following the 1997 discovery of oil impregnation at Asuk.

The marine slope channel sandstones were studied in a possible Campanian succession exposed on the northern slopes of Aaffarsuaq between Qilakitsoq and Tunoqqu. A major unconformity separates the slope deposits from the deltaic deposits of the underlying Atane Formation. The boundary with the overlying ?Maastrichtian–Paleocene sediments is less distinct because the nature of the ?Campanian sediments is very similar to the sediments above and interpretation of the exact position of the boundary must await a detailed palynostratigraphic analysis. The ?Campanian marine

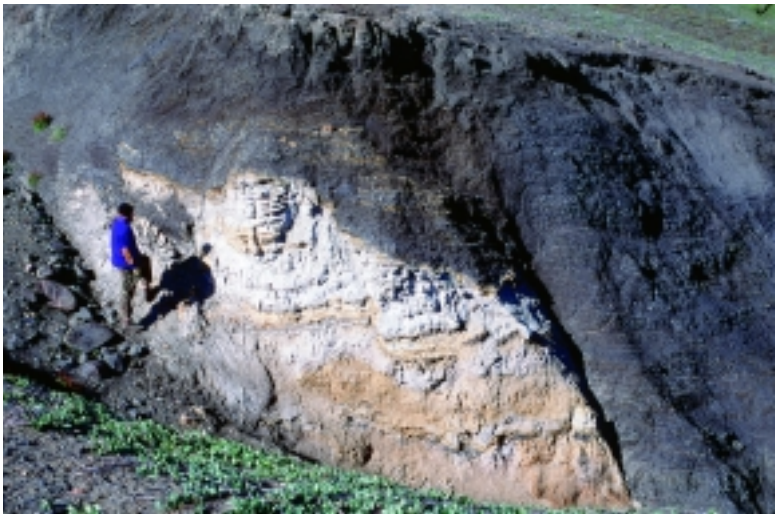

Fig. 3. Mid-Cretaceous sandstones of the Atane Formation unconformably overlain by Paleocene marine mudstones. A thin conglomerate separates the sandstones from the mudstones above. A normal fault showing a downward vertical displacement of the Paleocene mudstones by *c*. 20 m occurs in the right side of the picture. The yellow colour of the sandstones is due to oil staining. From Asuk at the north coast of Disko.

Fig. 4. Incised valley sandstones of the Paleocene Quikavsak Member. The valley is 190 m deep and *c*. 2 km wide and cuts into mid-Cretaceous fluvio-deltaic deposits of the Atane Formation. The valley sandstone is succeeded by offshore marine mudstones. Paatoot at the south coast of Nuussuaq.

slope sediments consist of mudstone, thinly interbedded sandstone and mudstone, and coarse-grained slope channel sandstones (deposited from high and low density turbidite currents), and sandy debris flows and slumps. The lower unconformity and the general chaotic nature of the sediments suggest syn-tectonic deposition during a previously unknown tectonic event in the Campanian. The ?Campanian slope sandstones constitute potential reservoir units, but the predictability is low due to the chaotic nature of the sediments.

During the Late Maastrichtian the area became tectonically unstable and was subjected to block faulting. Several phases of uplift, valley and canyon incision and infilling occurred, continuing into the Paleocene. This tectonic phase has been related to the earliest influence in the area of the Iceland mantle plume at the base of the lithosphere (Dam *et al.* 1998). The Paleocene unconformity was studied at Asuk on the north coast of Disko and at Paatoot on the south coast of Nuussuaq. In the Asuk area, the unconformity is succeeded by a conglomerate or by a thin sheet of shoreface deposits separating the mid-Cretaceous Atane Formation from unnamed Paleocene mudstones above. At this locality oil staining was found in the uppermost 3 m of the sandstone below the unconformity and the mudstones seem to form the main seal (Fig. 3).

At the south coast of Nuussuaq the unconformity is marked by a major valley incision (Fig. 4; Dam & Sønderholm 1998). The seaward extensions of these valleys into deeply incised marine canyons are regarded

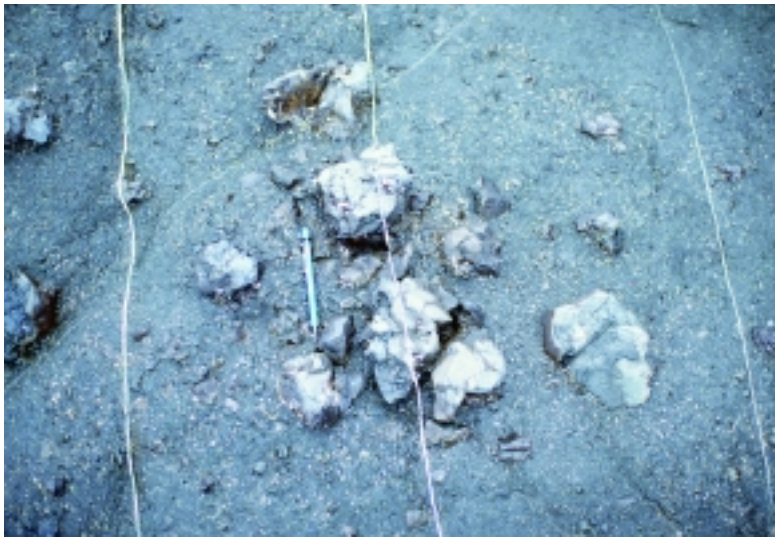

Fig. 5. Young generation of N–S trending mineralised fractures cutting through clasts in the hyaloclastites. From the Sikillingi area, Nuussuaq. Pencil for scale.

as one of the best potential reservoir units in western Nuussuaq (Kristensen & Dam 1997; Sønderholm & Dam 1998). A number of detailed sections were measured across the unconformity and a series of small-frame colour photographs were taken from a helicopter with 60% overlap to provide stereoscopic models that are usable for multimodel photogrammetrical analysis. Within the incised valley fill a possible lacustrine source was sampled. Preliminary analyses show TOC values between 7% and 11%, and HI values up to 175.

Studies of Tertiary basalts

The oldest Tertiary volcanic rocks in West Greenland have been shown to host a major part of the discovered oil seeps and impregnations. In order to study the relationships between volcanism and the development of sedimentary basins, and in particular to study the progression of the volcanic rocks at the time of the initiation of volcanism, the oldest lavas, volcanogenic conglomerates and hyaloclastites on Nuussuaq and Hareøen were sampled for chemical and lithological analysis. In addition the lateral lithological variations were documented through systematic stereo-photography in order to provide material for multi-model photogrammetrical analysis. This investigation is expected to enable a three-dimensional reconstruction of the early volcanic basins to be made which will also include the thick volcanic successions encountered in drill cores on western Nuussuaq.

Structural studies

The structural studies were concentrated in areas around Bartschiakløft, Nuusap Sanningasua and Hareøen. Detailed studies were carried out in the Marraat area with special interest on the intense fracture and joint system in relation to the zeolite zonation. There is a correlation between intensity of mineralised veins, presence of dykes and zeolite zonation, as well as a difference in orientation between veins and joints with zeolite zonation and those without.

Structural profiles were made in the Nuusap Sanningasua area in order to study the relative chronology of dykes and veins in the area. It is possible to establish chronological relations between at least three generations of dykes and veins, where the youngest of the mineralised veins often appear to cut through clasts in the hyaloclastites (Fig. 5).

Systematic sampling of dykes at Nuusap Sanningasua was carried out in order to make a geochemical correlation between dykes and specific lava successions and to obtain absolute ages for the dykes. There is a close relationship between appearance of dykes and the concentration of calcite-filled veins in the hyaloclastites. Furthermore there is a difference in orientation of dykes between areas with joints and mineralised veins and areas without.

Structural studies in Bartschiakløft have revealed a complex system of faults that can be divided into at least three directions. Some fault trends, also visible on the offshore seismic data, may be related to the rifting phase of the opening of the Labrador Sea. Further studies and

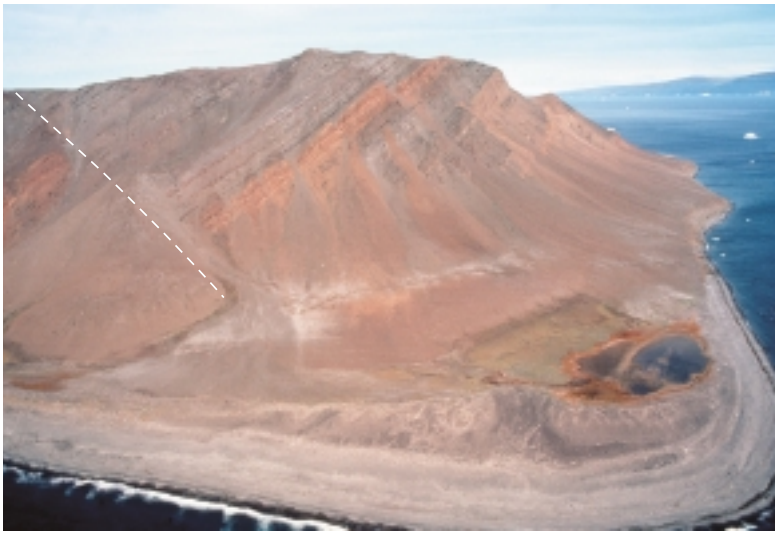

Fig. 6. View of the 300 m high part of Hareøen showing an E–W trending fault displacing the lower part of the Vaigat Formation.

correlation between onshore structural data and offshore seismic data are necessary in order to establish a structural model for the development of the Nuussuaq Basin.

The stereo-photography programme referred to above was extended to areas around Sikillingi, Marraat, Bartschiakløft, Kuugannguaq and Hareøen (Fig. 6).

Studies of hydrothermal alteration

A new research programme was initiated in 1997 to assess the nature of hydrothermal alteration within the Tertiary lavas of Disko, Nuussuaq, and Hareøen. The main aims of this work are: (1) identification and mapping of regionally extensive depth-controlled secondary mineral isograds throughout the province; and (2) documentation, sampling, and mapping of hydrothermal veins and replacement alteration in the Marraat area. These objectives were met through regional-scale mapping and outcrop-scale observations and sampling.

Investigations of regional alteration patterns concentrated on identification of regionally extensive zones characterised by secondary mineral assemblages dominated by zeolites. Similar sets of zeolite zones have been observed in other parts of the North Atlantic Tertiary igneous province (e.g. Walker 1960a, b; Jørgensen 1984; Neuhoff *et al.* 1997) where they are sensitive indicators of the thermal (Kristmannsdóttir & Tómasson 1978) and lithological structure (e.g. Walker 1960a) of the upper crust. The zeolite zones indicate the palaeothickness of the now partly eroded Tertiary flood basalts in the province, and make it possible to interpret the geothermal gradient in the lava series shortly after the eruption of the basalts. Systematic mapping of zeolite zones along the south-western, southern, eastern and north-eastern coasts of Disko, south-western Nuussuaq and Hareøen indicates that most of the exposed lavas have undergone regional low-grade metamorphism (< 100ºC based on the presence of the chabazite-thomsonite, analcime, and mesolite-scolecite zones) in response to geothermal gradients ≤ 30ºC/km. Reconnaissance mapping along the southern coast of Nuussuaq west of the Itilli fault zone suggests that these lavas were altered at significantly higher temperatures (≥ 100ºC based on exposures of laumontite and stilbite-heulandite bearing lavas) and tilted westward after regional metamorphism. Assuming that the geothermal gradient is ≤ 30°C/km, then the zeolite zones present in the area indicate an erosion factor less than expected.

Detailed outcrop and kilometre-scale investigations were conducted in order to determine the conditions, relative timing, structural environment, and relationship to oil migration of various stages of alteration present in the Marraat region. Early regional alteration (dominated by thomsonite with local development of chabazite and analcime) fills primary pore spaces in the lavas and is overprinted by several prominent vein sets. The most prominent of these veins in outcrop are filled with silicate-bearing (xonotlite, pectolite, or natrolite) mineral assemblages and occur together in infrequent swarms as reported by Karup-Møller (1969). Other less prominent but more common veins filled with quartz or calcite or both frequently post-date the silicate veins. Certain carbonate veins contain petroleum and appear

to be conduits for migration; lavas hosting these veins are petroliferous and exhibit extreme CO_2 metasomatism that replaced (often pseudomorphically) earlier Ca-silicate alteration with silica-clay-carbonate assemblages.

Preliminary field results and planned analysis of samples collected in 1997 will provide fundamental data for assessing the physical and chemical nature of petroleum systems in West Greenland. Regional alteration patterns (i.e. zeolite zones) constrain the pre-erosional thickness of the lava pile, thermal gradients during regional alteration, and the timing and orientation of structural deformation within the lava pile (cf. Neuhoff *et al*. 1997) necessary for evaluating the burial and thermal history of the underlying sedimentary basin(s). Determination of vein mineralogy, orientation, frequency and timing promises to provide at least semi-quantitative constraints on the magnitude, direction and composition of groundwater migrating through the reservoirs. Lastly, the apparent spatial and causal relationships between petroleum-bearing veins and carbonate-metasomatism may offer a new exploration tool for identifying petroleum migration paths in basaltic reservoirs.

Commerical exploration by grønArctic Energy Inc.

Compared to the very active year of 1996 when grønArctic carried out a major airborne geophysical survey and drilled a *c*. 3 km deep exploration well, GRO#3, on Nuussuaq (see Christiansen *et al*. 1997), the level of commercial exploration activity was very low in 1997 and did not include any field work, geophysical surveys or drilling. In 1997 grønArctic gave up their license that covered 1011 km^2 on eastern Disko, together with a few valleys in central and northern Disko. By the end of 1997 grønArctic had relinquished further areas on Nuussuaq so the company's remaining licence area is reduced to 390 km^2.

Future work

Field work, analytical studies and regional interpretation of the development of the Nuussuaq Basin will continue in the coming years, and will include a variety of geological disciplines. Results from the sedimentological, structural, volcanic and zeolite minerals studies will add considerable knowledge to the understanding of the petroleum system of the Nuussuaq Basin, especially with respect to source and reservoir rocks and timing of trap formation and maturation.

Considerable analytical effort will be used to study the distribution and origin of the different oil types, and their implications for the exploration potential of the Nuussuaq Basin as well as for the neighbouring offshore basins. Additional field work may add new localities to the encouraging pattern that has been demonstrated so far. Infill sampling is necessary in some areas whereas areas without previous evidence of oil shows (e.g. on western Disko) will be checked. The presence of sediment-contaminated volcanic rocks with magma-modified carbon and sulphide-rich sedimentary xenoliths along the entire west coast of Disko indicates the existence of marine carbonaceous sediments beneath the basalts west of the Disko gneiss ridge over very large areas. This makes western and south-western Disko a natural target for systematic 'oil hunting' in the future.

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