Geophysical and petroleum geological activities in the Nuussuaq – Svartenhuk Halvø area 1994: promising results for an onshore exploration potential

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After the successful completion of the 1993 field work and drilling programme in the Marraat area on western Nuussuaq (Fig. 1), including a subsequent logging and geophysical programme (see Christiansen *et al.*, 1994a, b; Dam & Christiansen, 1994), a new picture of onshore exploration opportunities has started to develop.

Previously the onshore basins were only considered to have a minor exploration potential, if any at all. However, the Disko–Nuussuaq–Svartenhuk Halvø region has been an important study area because many of the key parameters (sedimentological, stratigraphical and organic geochemical data from the excellent outcrops) may be obtained for predicting the distribution of reservoir and source rocks in the neighbouring major offshore basins in North-West and West Greenland (Christiansen *et al.*, 1992, 1994c).

The negative view of the onshore potential was mainly based on an inferred limited thickness of the sedimentary succession and lack of demonstrated source rocks for oil. Furthermore, the overlying Tertiary volcanic rocks are often several kilometres thick and difficult to penetrate by geophysical methods or drilling. Finally, many areas have a rough mountainous terrain cross-cut by glaciers and are in practice inaccessible for geophysical or drilling programmes.

However, field work in 1991–94, drilling of the Marraat-1 well in 1993, a geophysical survey in 1994 by the Geological Survey of Greenland and collaboration partners and commercial drilling activities in 1994 have changed this picture; commercial exploration activities will continue in the summer of 1995.

The break-through was the discovery of oil-filled vesicles in basalt in the Marraat area on western Nuussuaq in August 1992 (Christiansen, 1993; Christiansen *et al.*, 1994a, b). In 1993 the oil impregnation was found to be more extensive than first realised, and was furthermore observed in vesicular zones throughout the uppermost 90 m of the Marraat-1 core. The search for surface showings of oil was continued in 1994, and scattered occurrences of oil have now been found over an area of 8 × 5 km (Fig. 2).

The oil observed at the surface and in the Marraat-1 core has the same source; a characteristic organic geochemical composition suggests an early mature Tertiary deltaic source rock (Christiansen *et al.*, 1994b, unpublished GGU data). Although this source rock has not yet been located, and there is still little information on migration pathways, reservoir units and traps, it seems more and more likely that petroleum accumulations may exist in the subsurface of Nuussuaq.

The 1994 field programme aimed at solving a number of other problems in this context, some of them relevant for the Marraat area only, others relevant for assessing the potential of deeper sedimentary successions throughout Nuussuaq, and in particular for assessing the potential of the offshore basins. The main aims of the 1994 work are summarised below:

- To obtain a better structural model of the Marraat area by surface mapping and geophysical studies.
- To map the extent of oil impregnation in the Marraat area and extend sampling for continuation of the organic geochemical programme.
- To study the hydrothermal alteration history of the oil-impregnated as well as the 'dry' volcanic rocks.
- To continue the already extensive studies of the stratigraphy and structure of the volcanic succession including sampling for a palaeomagnetic study.
- To study the seabed in the nearshore areas with an echo-sounder and a side-scan sonar, to obtain data for lithological mapping and structural analysis and to find evidence of seepage of oil and gas.
- To carry out a geophysical programme (reflection and refraction seismic, transient electromagnetics, gravity, magnetics) along the south coast of Nuussuaq to obtain information on the total thickness and nature of the deeper part of the sedimentary succession, and if possible to define the configuration of the underlying basement.
- To carry out a geophysical programme along the south-west coast of Umiivik bay on Svartenhuk Halvø to obtain information on the total sedimentary thickness and the thickness of the marine shale succession for planning of a stratigraphic well in 1995 or later.

The field programme took place in a period of approximately one month from early July to early August and involved a total of 18 persons; these were mainly from

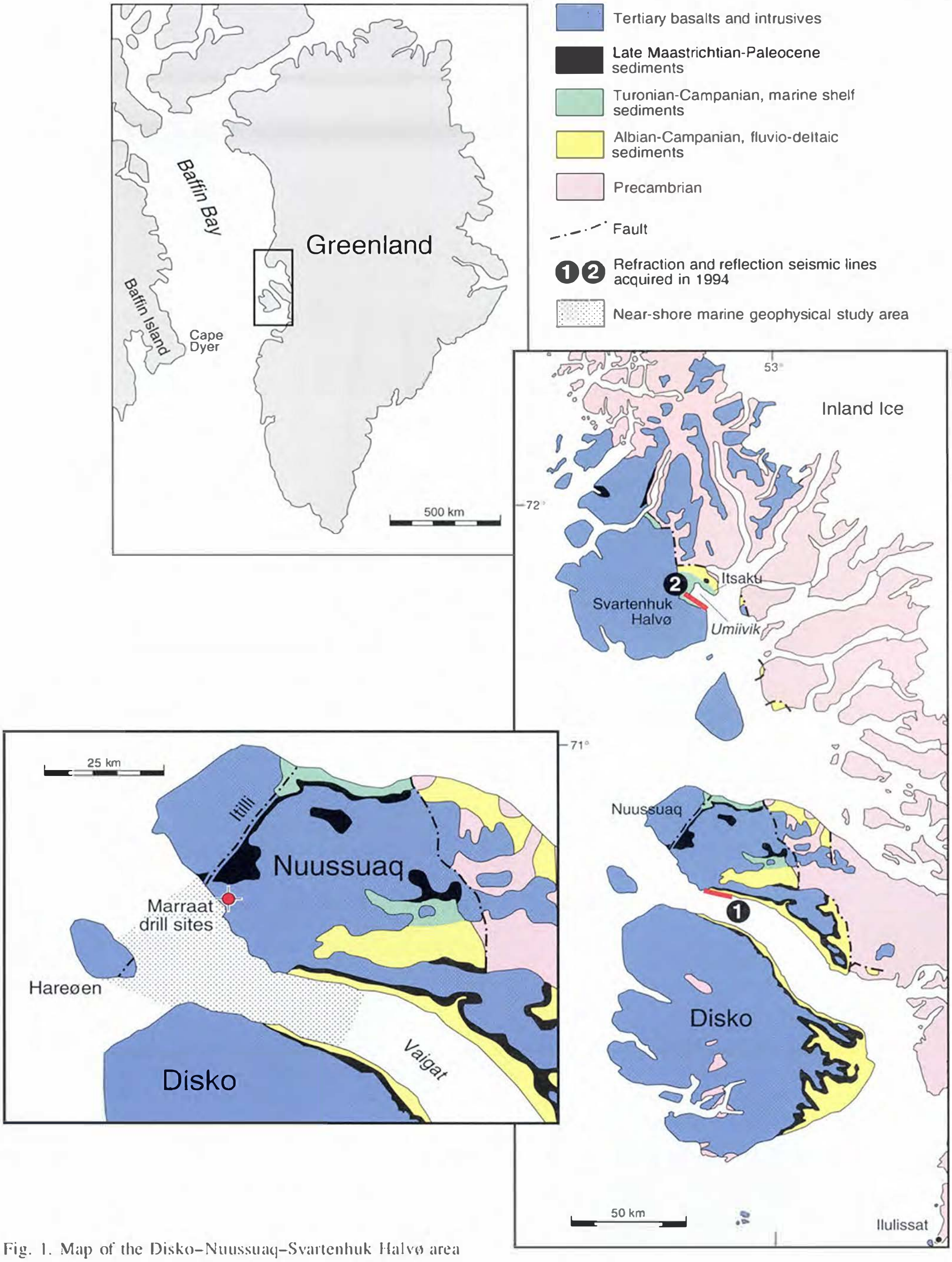

Fig. 1. Map of the Disko–Nuussuaq–Svartenhuk Halvø area showing location of onshore and nearshore geophysical and geological study areas.

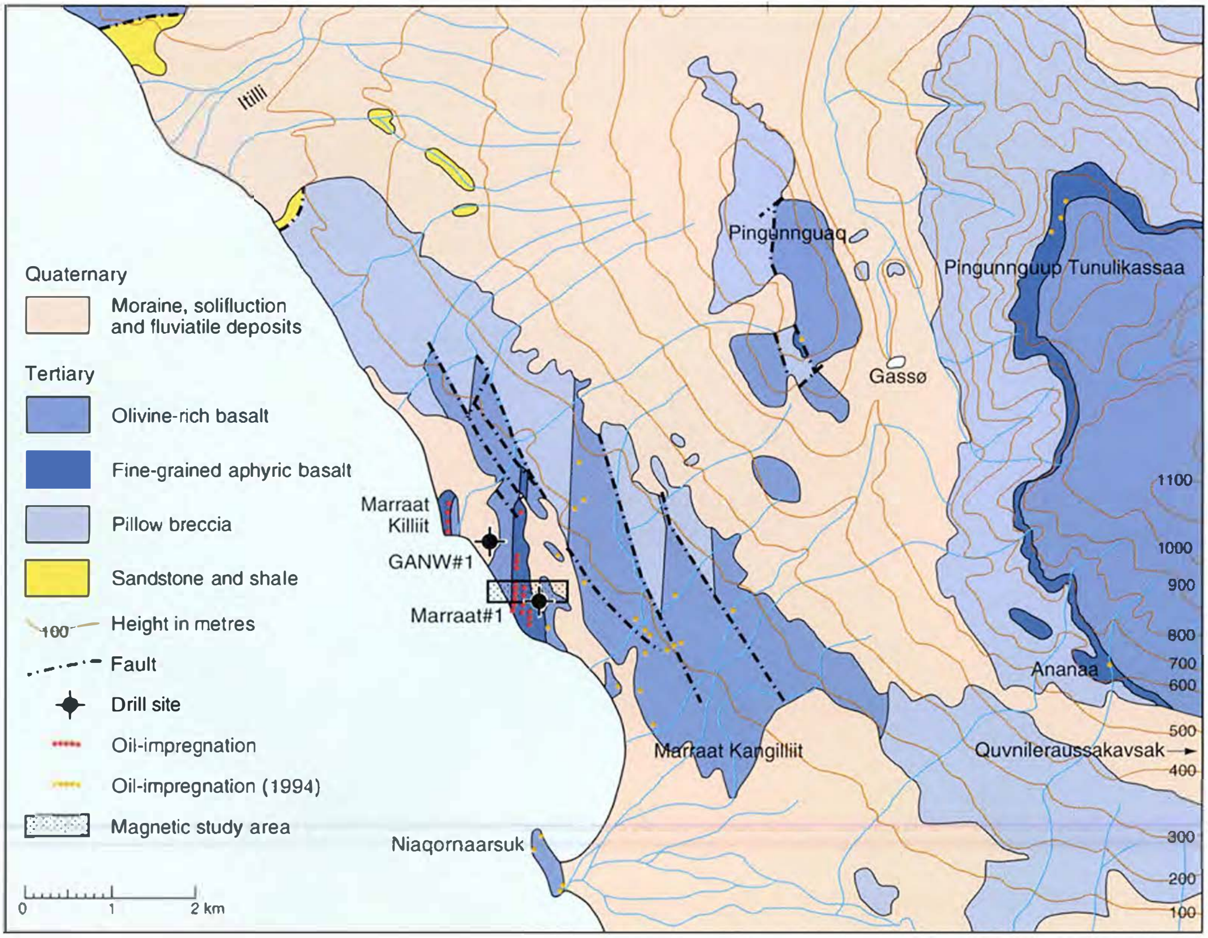

Fig. 2. Map of the Marraat area based on Henderson (1975).

GGU but also included collaboration partners from the Geological Museum and Geological Institute at the University of Copenhagen and from the Geophysical Department at the University of Aarhus, as well as consultants.

Field work in the Marraat area

Structural studies

The Marraat area was mapped in considerable detail (1:5000) in 1971 and 1972 (Henderson, 1975). The results of this mapping were compiled and published as a 1:100 000 geological map sheet (70 V.1 N Agatdalen; Rosenkrantz *et al.*, 1974). Many of the critical localities on the 1:5000 field maps were checked during the 1994 season, especially with respect to structural style and orientation of faults, dykes and major fracture zones.

The general geological picture, with basalts dipping 10–20° towards the east and cross-cut by numerous NNW–SSE trending faults with a steep westerly dip, was confirmed. By concentrating on distinct flows or tops of flows in some of the better exposed areas, it was observed that the intensity of faulting is higher than indicated on the original field maps. However, most of the area is relatively poorly exposed and the homogeneous nature of the volcanic breccias in particular makes detailed mapping of the faults very difficult.

Extent of oil impregnation

The area with observed oil impregnation at the surface was considerably enlarged during the 1994 field season from the few square kilometres previously known to an area of at least 8 × 5 km (Fig. 2). In total more that 50 individual localities have so far been recorded and sampled. These localities are distributed within a large number of fault blocks. It is particularly interesting that oil-impregnation was recorded at high altitudes at Pingunnguaq (~750 m) west of the N–S fault that is thought to run through the Gassø valley, and also east of this fault at

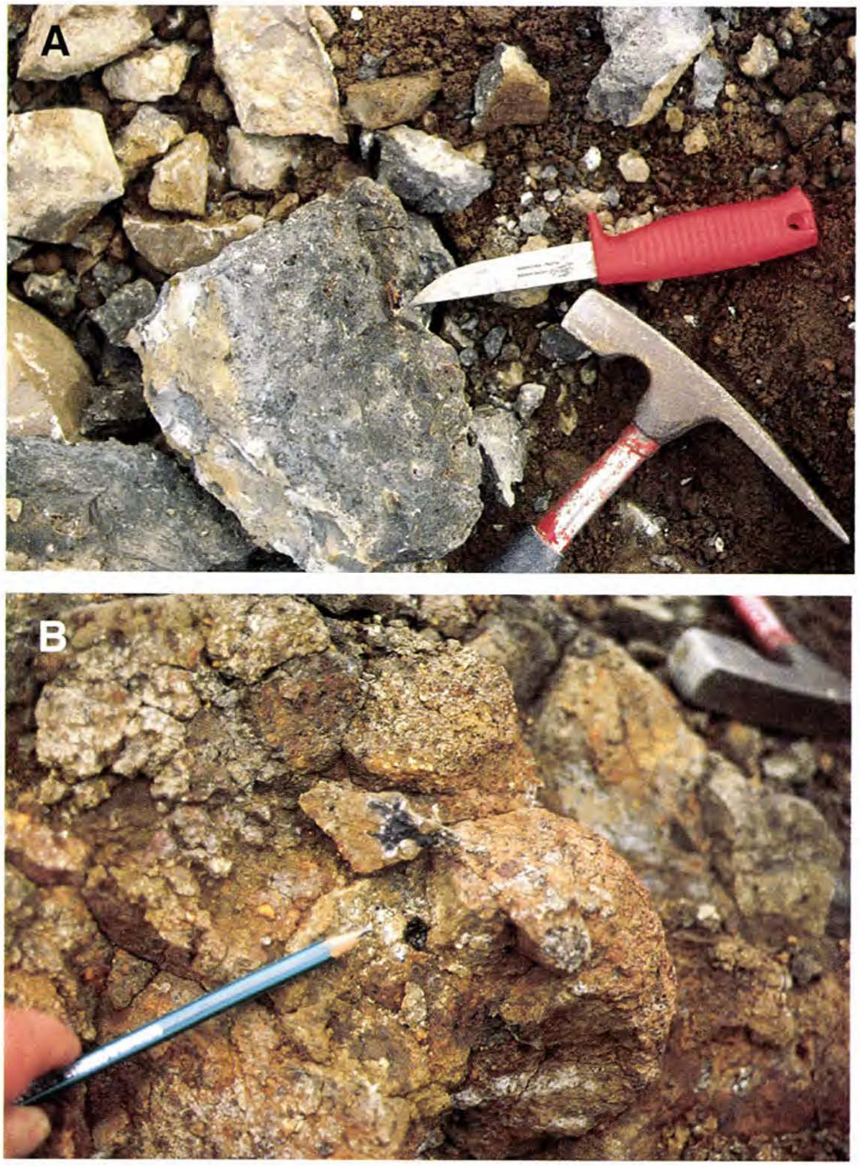

Fig. 3. A: Vesicular lava with waxy bitumen (near top of Pingunnguup Tunulikassaa, 1050 m above sea level). B: Vesicular lava with black solid bitumen (approx. 1 km east of the Marraat-1 drill site).

Pingunnguup Tunulikkassaa (~1050 m), Ananaa (~600 m) and at Quvnileraussakavsak (400–460 m) (Fig. 2). The three latter localities are probably situated within the same large fault block which shows a 5–10° eastward dip of the basalts.

By far the greater part of the oil impregnation is found within the vesicular tops of a number of lava flows consisting of aphyric sediment-contaminated basalt. This type of lava is easily identified in the field due to its yellowish to orange weathering colour. The main reason for the concentration of oil in these flows seems to be a higher porosity and especially permeability related to a higher concentration of fractures (more brittle nature of these silica-enriched rocks) compared to the picrites, olivine basalts and pillow breccias. The oil impregnation is typically observed as hard or soft, solid black bitumen and more brownish wax in large vugs, vesicles and fractures (Fig. 3). Most of the bitumen has a strong petroliferous odour and may flow at normal indoor temperatures.

In addition to sampling for organic geochemical analysis a large number of samples were collected for a study of the hydrothermal minerals which fill vugs, vesicles, veins and fractures in the volcanic rocks. Most of these minerals clearly predate the oil migration.

Volcanic stratigraphy and palaeomagnetism

The studies of the stratigraphy, structure and petrology of the volcanic succession on western Nuussuaq were continued in 1994. A number of sections were sampled in detail

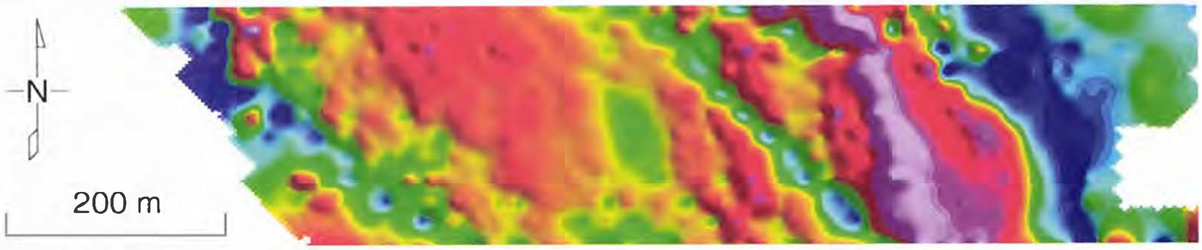

Fig. 4. Examples of magnetic map from the Marraat area. Note that several geological features typical of the area can be seen: dykes (some reversely magnetised), faults, and edges of inclined basalt flows tilted by faulting. Magnetic data acquired and compiled by L. Thorning, GGU.

for petrographic and geochemical analysis in order to support the correlation of volcanic units mapped with the aid of multi-model photogrammetry (Dueholm & Pedersen, 1992; Pedersen *et al.*, 1993). Furthermore, a systematic sampling programme for palaeomagnetic studies was carried out, aiming at a complete coverage of the lower part of the Vaigat Formation. Results from this study will be particularly useful for correlation and dating of the volcanic sequence and will also provide important data for interpretation of magnetic surveys.

Near-shore marine geophysics

The main objective of the near-shore marine geophysical programme was to obtain bathymetric data from the poorly known Vaigat sound; this will facilitate planning of further geophysical surveys in the future including various shallow geophysical surveys and conventional seismic acquisition. Studies of the morphology of the sea bottom are important for geological mapping of faults and lithology and may also provide evidence of oil and gas seepage.

The near-shore areas off Marraat, north-east to Hareøen and in Vaigat were studied by echo-sounder (with a total of 575 km) and a side-scan sonar (total of 135 km; Fig. 1).

A number of fault zones and various volcanic and sedimentary units have been mapped (I. Salomonsen, 1995; unpublished data). Unfortunately it was not possible to demonstrate seepage, although this may be due to dispersed ice in the uppermost water layers.

Onshore geophysics

A variety of geophysical methods were used to study western Nuussuaq and eastern Svartenhuk Halvø, including both refraction and reflection seismic, magnetic and gravity measurements and transient electromagnetic methods. The first processing of the seismic data has been completed, but the remaining data are still being processed and detailed reports will be presented elsewhere.

Gravity and magnetic data were acquired along the Nuussuaq seismic line and farther along the coast to the Marraat area (Fig. 1) to study whether these data could be used to extrapolate the seismic results. In the Marraat area (Fig. 2) it was found that a dense grid of magnetic measurements (e.g. 10 m × 20 m) can be used to map lineaments such as faults and dykes (Fig. 4). Although this method is time-consuming, it seems promising for structural mapping of selected key areas, e.g. around potential drill sites.

Transient electromagnetic methods were also tested along the two seismic lines and in the Marraat area. Unfortunately, no significant results were obtained, probably due to saline groundwater under the loop because of the position close to the sea.

Table 1. Processing parameters

1. import field records
2. common-midpoint sorting
3. trace edit
4. field statics
5. spherical divergence correction
6. mute first breaks
7. surgical mute
8. bandpass filter (zero phase): 20Hz (24dB/oct) – 80 Hz (24dB/oct)
9. NMO correction (velocities from contoured velocity spectra and constant velocity stacks)
10. trace equalisation (rms amplitude, window: 0–4000 msec)
11. surface consistent residual statics (correlation window 300 to 1000 msec, max. shift: 10 msec)
12. trace mix (shots) (3 adjacent, weight: 1–1–1)
13. CMP stack (maximum fold: 15)
14. spiking deconvolution (autocorrelation window: 0–4000 msec, operator length: 75 msec)
15. time variant filter:

0 – 1500 msec	10–15–80–85 Hz
1500 – 2500 msec	10–15–60–65 Hz
2500 – 4000 msec	10–15–40–45 Hz

Four different final stack displays were produced combining processing steps 12 and 14.

Fig. 5. Geophones and seismic cables at the geophysical camp on Svartenhuk Halvø.

Seismic acquisition and processing

A programme comprising both refraction and reflection seismic lines was designed in collaboration with a seismic consultant (Rambøll, Hannemann & Højlund A/S) based on the available geophysical information (Sharma, 1973; Elder, 1975). As helicopter support was not available for the seismic operation, the two seismic lines were positioned along the coast where there is often a fairly flat beach (Fig. 5).

Data were acquired along a 13 km line on the south coast of Nuussuaq and an 11.5 km line on the south-west coast of Umiivik bay on Svartenhuk Halvø using differential GPS for positioning (Fig. 1). For the refraction work a distance of 110 m between the geophone groups was used and the geophones were placed perpendicular to the line. A group distance of 55 m with the geophones in-line was used to acquire the reflection data. A 120-channel receiver and a shot spacing of 220 m mean that the maximum fold of the reflection data is 15. The seismic source for both the refraction and reflection studies was dynamite placed in the sea along the shore. Refraction shots had a maximum offset of 25 km.

A barge was used to transport the seismic equipment from Ilulissat/Jakobshavn, and two rubber dinghies and two three-wheeled Honda motorcycles proved to be very efficient for moving the relatively heavy equipment along the coast.

Processing of the seismic data was carried out by the seismic consultant in consultation with GGU geophysicists. Details of the processing sequence are given in Table 1. Muting was found to be critical, and the unexpectedly high stacking velocities were checked carefully. Results from the refraction seismic studies support the high velocities. Testing of deconvolution after stack combined with trace merging showed that no single sequence brought out all the features visible at different two-way times on the Nuussuaq line, and eventually four displays of the line using different combinations of parameters were made. The lines have not yet been migrated.

Interpretation of the Nuussuaq seismic line

A final stacked section from the south coast of Nuussuaq is shown in Fig. 6. The data quality is fairly good and strong reflectors can be seen down to about 3.5 seconds two-way-traveltime (TWT). Twelve horizons have tentatively been identified, five of which may be unconformities. Depths shown on the right hand side of the seismic section (Fig. 6) have been compiled from the stacking

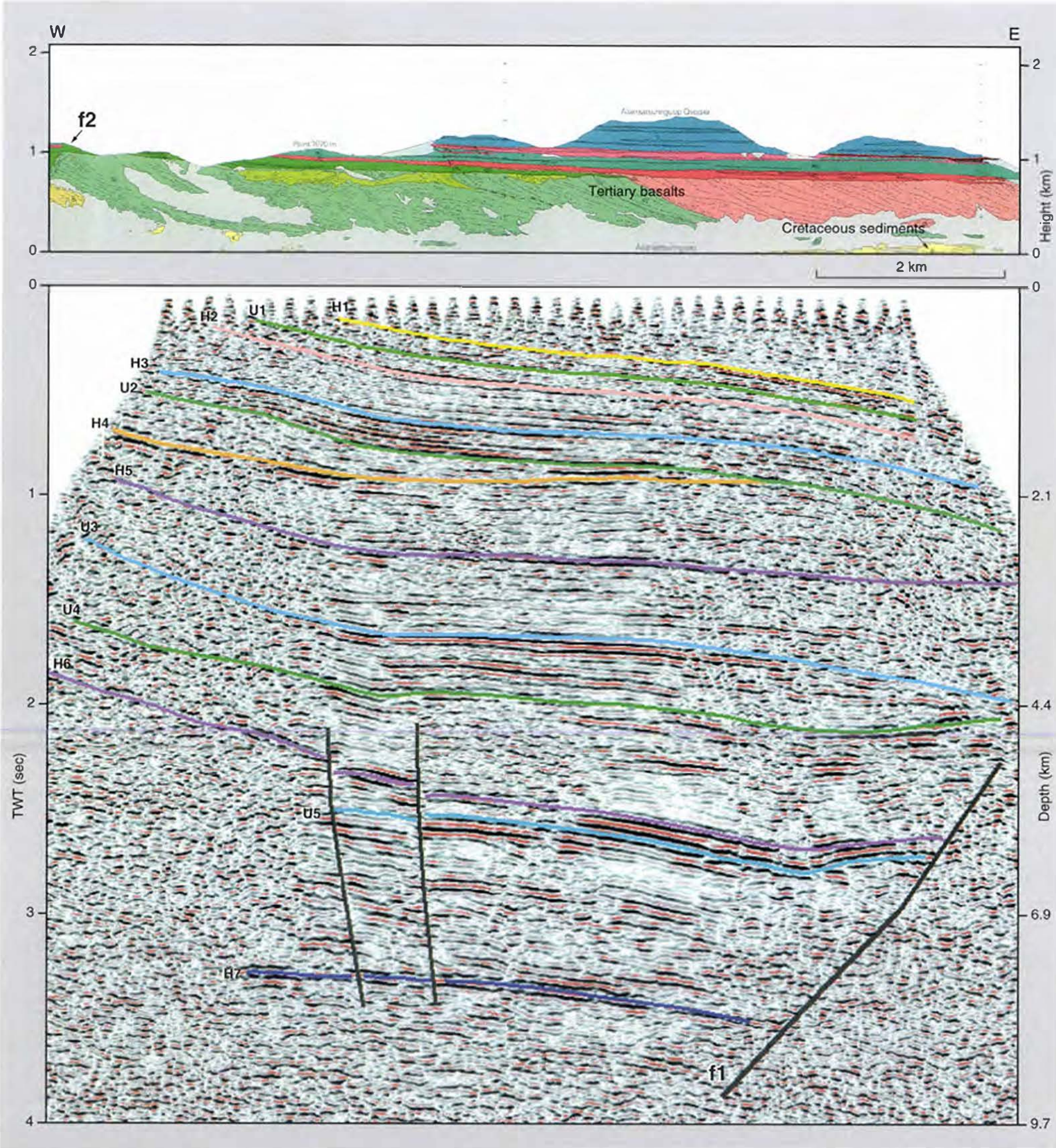

Fig. 6. The final stacked seismic section along the south coast of Nuussuaq with the corresponding part of the geological section shown at about the same scale with no vertical exaggeration (Pedersen *et al.*, 1993). Note that strong reflectors can be seen down to about 3.5 sec TWT. See text for further explanation.

velocities (Fig. 7). Two distinct trends in the velocities can be seen above and below about 1 sec TWT. Below 1 sec TWT the increase in average velocity with TWT is significantly slower than the rate of increase above 1 sec TWT. This change from one trend to the other is approximately where an angular unconformity (U2) can be seen.

In general the section shows a sedimentary succession dipping 6°–16° towards the east, which agrees with the structural information at the surface where non-marine Cretaceous sediments are exposed. What may be a large fault can be interpreted below 2.5 sec TWT on the eastern part of the section (Fig. 6; f_1). The extrapolation of this fault reaches the surface at Nuuk Killeq where a change of about 400 m in altitude of the base of the Tertiary sedi-

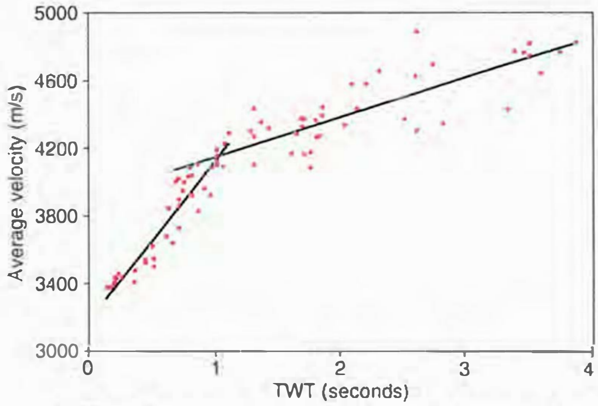

Fig. 7. Plot of average velocities versus two-way-traveltime (TWT). Note the two distinct trends in the velocities above and below about 1 sec TWT.

ments is known (Pedersen *et al.*, 1993). At the westernmost part of the section a fault down-throws the basalts to the west (Fig. 6; f_2). This locality is just west of the data coverage on the seismic line. It is therefore possible that the seismic section was acquired on a rotated fault block between these two faults.

The large thickness of sediments shown on Fig. 6 was not expected, because the stratigraphic thickness of the exposed non-marine Cretaceous is only about 2–3 km and older sediments are not known from outcrops in the Nuussuaq area.

Six units defined by five unconformities (U1-U5) have been recognised, of which U2 and U5 are the most prominent (Fig. 6). It is possible that the marked change in average velocities (Fig. 7) takes place at U2, rather than at a constant TWT. If so, this would indicate that U2 marks a significant change in the succession, possibly the base of the Cretaceous.

What lies below U2 can only be a matter of speculation. U3 may not mark a true unconformity, but could be a thin sill cutting across the sedimentary succession. U4 is a fairly weak unconformity, and the first major angular break below U2 is U5. It is very probable that most of the reflections from the interval down to U5 come from sediments. U5 is at a depth of about 6 km (Fig. 6). The sediments between U2 and U5 could be Cretaceous, perhaps corresponding to the Appat and/or Kitsissut sequences offshore (Chalmers *et al.*, 1993). Alternatively, they could be Ordovician limestones comparable to those exposed in eastern Canada (Bell & Howie, 1990), erosional remnants of which are found in Greenland (Stouge & Peel, 1979). However, geochemical fingerprints from the Tertiary basalts show that they have definitely passed through clastic and organic-rich sediments but there are neither geochemical nor petrographic fingerprints from carbonate sediments (A. K. Pedersen, personal communication, 1995). It is therefore possible that the sediments between U2 and U5 could be completely unknown Mesozoic sediments.

What lies below U5 is not clear on geophysical evidence. It is possible that H7 is a peg-leg multiple between U3 and U5. If so, U5 appears to be basement at a depth of 5.5 to 6 km. If H7 is real, then there is a third succession below U5 about 2 km thick and basement lies at around 8 km depth. This deepest unit may not be sedimentary. A volcano 12 km north of the seismic section was fed from an upper-crustal magma chamber (L. M. Larsen, personal communication, 1995), and it is possible that the reflections from below U5 could come from such a feature.

Interpretation of the Svartenhuk Halvø seismic line

The seismic line on Svartenhuk Halvø was placed where black marine shales of Santonian age are exposed. The main objective of shooting the line was to estimate the depth to the base of the marine shales and to basement, to help planning of a stratigraphic bore hole. A final stacked section is shown in Fig. 8. It is difficult to assess the quality of this seismic profile, because there are few continuous reflections from below the mute zone which extends to about 250 msec TWT.

A strong, fairly continuous reflection, which shows a weak synclinal structure, can be seen along the total section at approximately 250–400 msec TWT, which corresponds to a depth of 600–800 m. Below this reflection, two strong reflections occur at the south-east end of the profile at 500 msec and 700 msec TWT. A few other weak reflections of limited lateral extent can also be seen. A diffraction pattern, which may indicate a fault throwing down to the north-west, can be seen to originate from around 200 msec TWT (Fig. 8; f).

It is possible that the fairly continuous reflection between approximately 250 and 400 msec TWT comes from the base of the marine shales. What lies below that is conjectural. It is possible that the marine shales lie on fluviatile sandstones of Early Cretaceous age similar to those exposed farther to the north-east on Itsaku. In that case the reflections at the south-east end of the line may come from sills intruded into these sandstones. It is known from other parts of the world, for example the Triassic of the northern Viking Graben (e.g. Pettersen *et al.*, 1988), that such sandstones can be weakly reflective internally and may produce no reflection when they lie on basement. Another possibility for the lack of reflectivity below 250–400 msec is that the marine shales may lie directly on basement; however, the number of reflections down to at least 700–800 msec at the north-west end of the line and to about 1400 msec at the south-east end makes this conjecture unlikely.

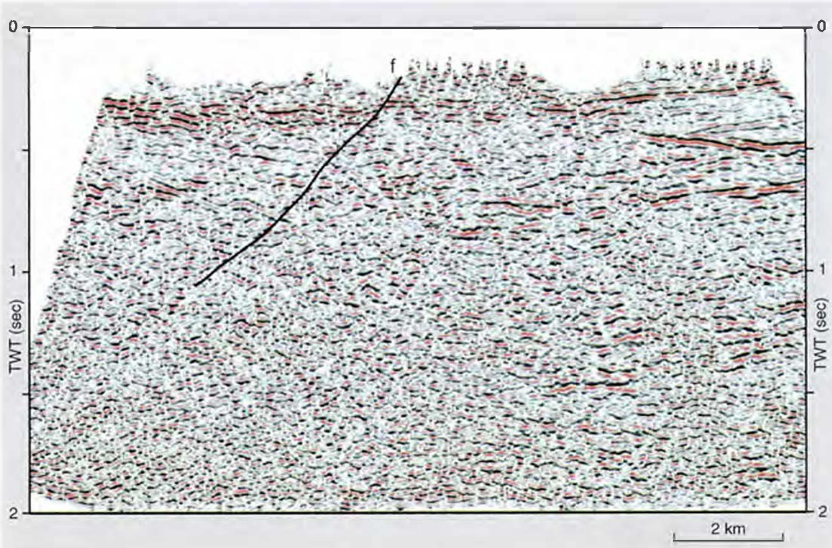

Fig. 8. Final stacked section from Svartenhuk Halvø. Note the strong, fairly continuous reflection along the total section at about 250–400 msec TWT, corresponding to depths of about 600–800 m depth. This reflector may represent the base of the marine shales. A fault (f) may be indicated by diffraction.

Drilling of commercial well

Shortly after completion of GGU's field work in the Marraat area a newly established Canadian company, grønArctic Energy Inc. of Regina, Saskatchewan, applied for a prospecting licence covering Nuussuaq west of longitude 52° W. After granting of this licence grønArctic drilled the GANW#1 well approximately 1 km north-west of GGU's Marraat-1 drill site (Fig. 2, Table 2). The well reached a depth of 800 m and was suspended with a view to re-entering in 1995; results are still confidential.

GGU personnel were present throughout the drilling period in order to take samples for geochemical analyses of sediments, gas and formation fluids. After completion of the drilling programme GGU took over the core which is now stored in Copenhagen. All data from the well are confidential, but may be released after the end of 1996.

During the autumn of 1994 grønArctic Energy Inc. negotiated the terms of an exploration licence with the Mineral Resources Administration for Greenland. This licence was granted in the spring of 1995, and as a consequence at least three slim holes to depths of more than 1000 m will be drilled in 1995. There will be at least one well in the Marraat area and at least one on the north coast of Nuussuaq.

Implications for the future

The results of the 1994 programme are very encouraging for future exploration and research activities both onshore and offshore West and North-West Greenland.

So far developments in the Nuussuaq area have been extremely fast compared to other regions in Greenland. A commercial exploration programme has started only two years after the discovery of the first oil-impregnated surface samples in 1992, and at least three wells can be expected in 1995. Furthermore, a sound background has been established for a stratigraphic drilling programme on Svartenhuk Halvø, with a view to discovery of a mid-Cretaceous oil prone source rock.

Table 2. Technical data from the grønArctic well

Well name:	grønArctic Nuussuaq West #1 (GANW#1)
Operator:	grønArctic Energy Inc. Regina, Saskatchewan, Canada
Drill contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada
Locality:	Marraat, Nuussuaq, West Greenland
Coordinates:	70°31′25″N, 54°13′01″W
Elevation:	14.6 m a.s.l.
Well spud date:	11 September, 1994
Rig release date:	5 October, 1994
Rig type:	diamond drill Longyear Fly-in 38
Hole diameter:	60 mm (2 $^{23}/_{64}$ inch) (BQ rod)
Core diameter:	36.5 mm (1 $^{7}/_{16}$ inch)
Total depth:	2625 ft (800 m), ~100% core recovery
Status:	suspended, planned to be re-entered in 1995
Formations drilled:	Lower Tertiary volcanics and sediments

Although the planned drilling activities in 1995–96 are onshore, the implications of an oil discovery or the documentation of a source rock will be of great importance for future offshore activities in North-West and West Greenland.

In order to tie the onshore drilling information to the offshore basins, a seismic programme in the Disko–Nuussuaq–Svartenhuk Halvø area has been proposed. This programme will also study the possible existence of a deep sedimentary basin in the region.

Acknowledgements. The Mineral Resources Administration for Greenland funded most of the field programme. Mobilisation of the base camp and the geophysical camps took place with the help of two local ships, *Maja S* and *Auvek* (with barge). Finn Steffens, Jørgen Danielsen, Ove Zeeb, Lars Christensen and Ove Larsen are thanked not only for good seamanship during these operations, but also for their hard work during the geophysical surveys. Falconbridge Ltd provided helicopter transport from Universal Helicopter. The seismic and electromagnetic equipment was provided by Rambøll, Hannemann & Højlund A/S (Carsten Ploug as consultant planned and directed the seismic and electromagnetic data acquisition), and the side-scan sonar was supplied by the Geological Survey of Denmark (using Peter Trøst Jørgensen as consultant).

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