Acquisition of high-resolution multichannel seismic data in the offshore part of the Nuussuaq Basin, central West Greenland

Christian Marcussen, James A. Chalmers, Holger Lykke Andersen,
Rasmus Rasmussen and Trine Dahl-Jensen

A high-resolution multichannel seismic survey (project *NuussuaqSeis 2000*) was carried out from 18 July to 2 August 2000 in the offshore part of the Nuussuaq Basin, central West Greenland using the Danish research vessel R/V *Dana* with seismic equipment from the Geological Institute, Aarhus University, Denmark. Funding for the project was provided by the Danish Energy Research Programme, the Bureau of Minerals and Petroleum, Nuuk, Greenland, the Geological Institute of Aarhus University and the Geological Survey of Denmark and Greenland (GEUS). After completion of the *NuussuaqSeis 2000* project, R/V *Dana* was used for a three-day coring project in Disko Bugt (see Kuijpers *et al.* 2001, this volume) before the ship returned to Denmark.

Background

Knowledge of the Nuussuaq Basin in central West Greenland (Fig. 1) has increased significantly since the discovery of extensive oil seeps on western Nuussuaq in 1992 (Bojesen-Koefoed *et al.* 1999). A number of geological and geophysical studies have been published and data from slim core drilling and exploration wells are also available. The existence of the oil seeps indicates that the Nuussuaq Basin is a petroleum basin in its own right, and not merely an accessible analogue to potential petroleum basins offshore (Bojesen-Koefoed *et al.* 1999). Seismic data acquired onshore in 1994 (Christiansen *et al.* 1995), followed by a seismic and gravity survey in 1995 in the fjords south and north of Nuussuaq, have greatly improved the general understanding of the structure of the basin (Chalmers *et al.* 1999a). Project *NuussuaqSeis 2000* – acquisition of high-resolution multichannel seismic data in the waters around Nuussuaq and Ubekendt Ejland – was designed to improve understanding of the shallow structure of the Nuussuaq Basin.

The seismic survey

Planning

Experience during seismic acquisition in earlier years in the same waters has shown that use of a long streamer (e.g. 3000 m) is likely to be prevented by the large numbers of icebergs. While usage of a short streamer makes it impossible to remove seabed multiples by traditional methods (e.g. F/K filtering), the relatively large water depths in the area of interest – between 400 and 800 m – make it possible to see up to 1.5 km of sediments before the first seabed multiple obscures the data. It was therefore decided to accept the limitations of a short streamer, and use high-resolution seismic equipment with a considerably smaller source but better resolution than conventional marine seismic equipment.

Prior to initiation of the survey, all available bathymetric data were compiled and plotted together with the planned lines as overlays to the published charts from the area. This showed that the bathymetry of parts of the survey area was poorly known. The planned survey consisted of 2013 km of priority 1 lines in Vaigat and Uummannaq Fjord plus 290 km of priority 2 lines over the areas underlain by basalt west of Nuussuaq and Ubekendt Ejland.

Seismic equipment

The seismic acquisition system used for the survey is owned by the Geological Institute of Aarhus University. It includes a 96-group, 594 m long hydrophone streamer with a 6.25 m group interval and two Geometrics R48 recording systems. The source consisted of a 4×40 in^3 sleeve-gun cluster. Navigation was controlled by Navipac software, and positioning was provided by an Ashtech G12 GPS receiver (see Table 1 for details). A Ramesses quality-control system is integrated in the acquisition system to provide real-time processing and display

Geology of Greenland Survey Bulletin 189, 34–40 (2001)

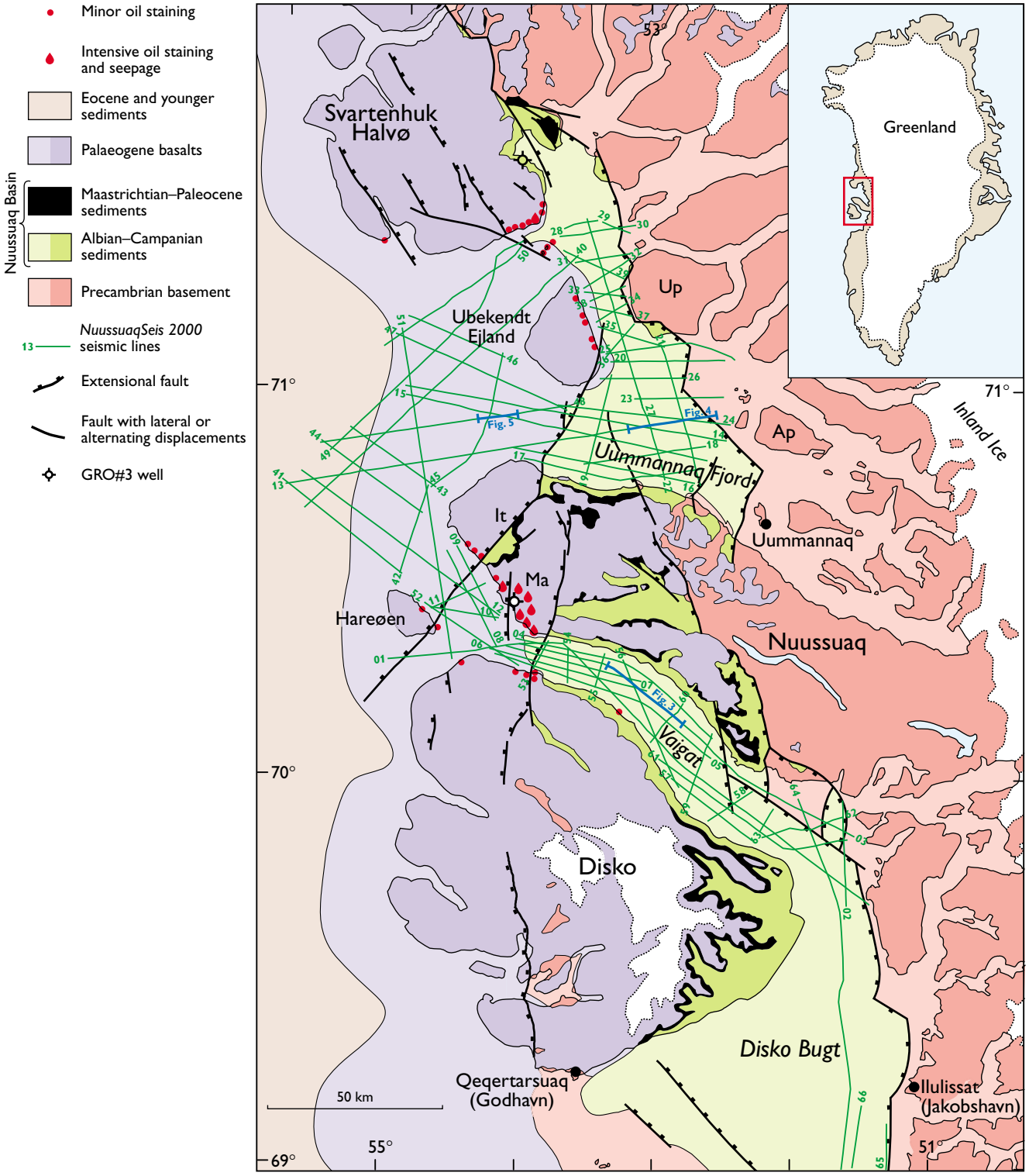

Fig. 1. Simplified map of the Nuussuaq Basin showing the geology onshore (dark colour tones) and offshore (light colour tones), place names used in text and the seismic lines acquired during project *NuussuaqSeis 2000*. The prefix GEUS00- is omitted from all line numbers. Location of the seismic examples in Figs 3, 4 and 5 are shown. **Ap**: Appat Ø, **It**: Itilli fault, **Ma**: Maarrat, **Up**: Upernivik Ø. White areas are ice. Modified from Christiansen *et al.* (2000).

Table 1. Acquisition equipment and parameters

	Equipment / Parameters
Source	4 x 40 in³ TI SG-I sleeve guns
Spacing between individual guns	50 cm centre to centre
Depth	3.5 m to centre of cluster
Pressure	120 bar
Streamer	HydroScience
Length	593.75 m (active section)
Towing cable length	90 m
Number of groups	96
Group interval	6.25 m
Group length	3.125 m
Streamer depth	3 m
Near offset	53 m
Shotpoint interval	5 sec ≈ 12.5 m
Recording system	2 Geometrics R48
	Sample rate: 1 msec
Record length	3072 msec
Delay	0 msec
Filters	Low cut: 10 Hz slope 24 db/oct
	High cut: 300 Hz anti-aliasing
Data format	SEG-D 8048 revision 0
Output media	IBM 3490 cartridge
Navigation	GPS - Ashtech G12 receiver
Magnetometer	Geometrics G866
Echosounder	Simrad EK 400

facilities. Due to technical problems, magnetic data were recorded only from line GEUS00-18.

A ProMax processing system from GEUS was installed on R/V *Dana* (Fig. 2); this system was used for test processing of the seismic data and hence gave valuable input for subsequent adjustments of the survey programme.

Data acquisition

A total of 2743 km of data were acquired during the 18-day survey, which was 20% more than planned (Fig. 1; Marcussen *et al.* 2001). During the entire cruise, the weather was effectively calm and therefore ideal for seismic acquisition. Icebergs, which were expected to be the main obstacles to seismic acquisition, were either relatively sparse, in which case it was possible to acquire data around them without significant problems other than the occasional move slightly off-line, or they were packed so densely that some areas were impossible to penetrate. The amount of time lost for equipment downtime was also small, a total of about 10 hours. Maintenance of equipment was mostly undertaken during extended line shifts.

Data were acquired in three areas: (1) the Vaigat area south of Nuussuaq; (2) the area of Uummannaq Fjord and the strait between Ubekendt Ejland and Upernivik Ø; and (3) the areas west of Ubekendt Ejland and Nuussuaq where basalts are exposed on the seabed. A preliminary interpretation of the data was made onboard as it became available throughout the survey. The primary purposes of the interpretation were to provide information for any necessary alteration of survey plans, to judge the quality of data, to provide input to processing on ProMax, and to develop models for subsequent more detailed interpretation.

Vaigat

Chalmers *et al.* (1999a) divided the Vaigat area, the sound between Disko and Nuussuaq, into three distinct parts. West of about 54°W, basalt is exposed at the seabed (Fig. 1). Between longitudes 54°W and 53°W, three large fault-blocks with thick, easterly dipping, Cretaceous sediments can be seen. The centre of the bathymetric channel is partly filled by flat-lying Holocene

Fig. 2. The Danish research vessel R/V *Dana* in Uummannaq Fjord during project *NuussuaqSeis 2000*.

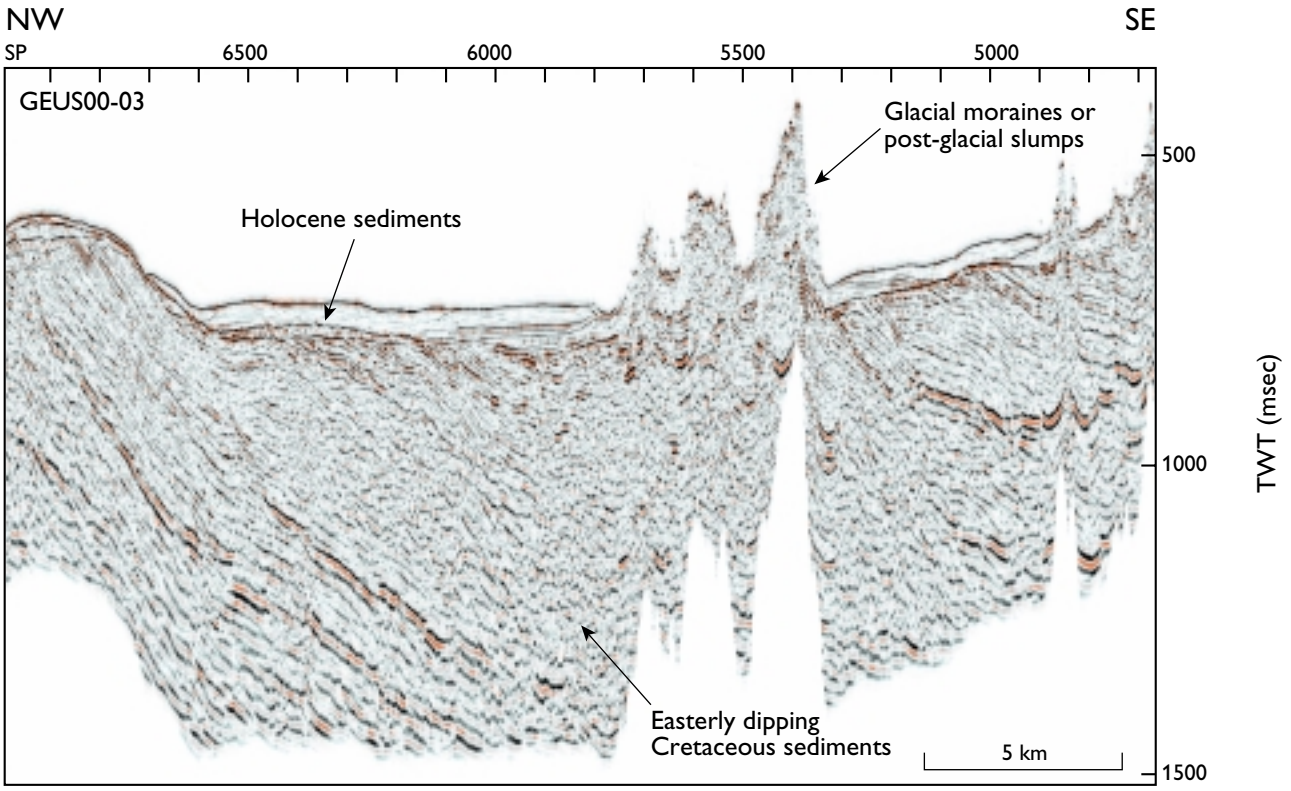

Fig. 3. Example of seismic data from Vaigat. Part of line GEUS00-03 showing easterly dipping Cretaceous sediments beneath flat-lying Holocene sediments with large glacial moraines or post-glacial slumps. Location shown in Fig. 1. **SP**: shot point.

sediments (Fig. 3). The area east of 53ºW is complex, with both large glacial moraines or post-glacial slumps and sills at and beneath the seabed (Fig. 3).

The first phase of the survey in Vaigat was carried out for the most part on the pre-planned lines. Since the iceberg density was low, the strategically most important data was acquired first over the known area of fault-blocks in western Vaigat. It became apparent during the acquisition of these first lines that the quality of the data was good to excellent in those areas without sills, large glacial moraines or post-glacial slumps at the seabed (Fig. 3).

Preliminary interpretation of the lines acquired in western Vaigat showed that the interpretation shown in Chalmers *et al.* (1999a) was essentially correct, and in the second phase of the survey in this area a number of lines were planned to cross the western part of the fjord within each fault-block to provide horizon ties between the lines along the fjord.

Eastern Vaigat has a complex structure, and the interpretation shown in Chalmers *et al.* (1999a) requires revisions. Additional lines were acquired to optimise new interpretations of the structure.

A few lines were acquired in the area off Maarrat between Nuussuaq and Hareøen in order to test whether correlation of the onshore geology and the results of the GRO#3 exploration well to the offshore areas was possible.

Uummannaq Fjord and the strait between Ubekendt Ejland and Upernivik Ø

The area north of Nuussuaq is characterised by large fault-blocks with thick, easterly dipping, Cretaceous sediments (Chalmers *et al.* 1999a). The fault-blocks are divided by faults that throw down to the west and can be identified as offshore extensions of faults known onshore (Fig. 2). To the east Precambrian basement is exposed, whereas west of the offshore extension of the Itilli fault basalt is exposed at the seabed.

Acquisition started in this area with line GEUS00-13, a long transect from west of Nuussuaq to basement outcrop west of Appat Ø. On the way into and across Uummannaq Fjord, it became apparent that there was a low density of icebergs in the outer fjord similar to that encountered in Vaigat, but icebergs were tightly

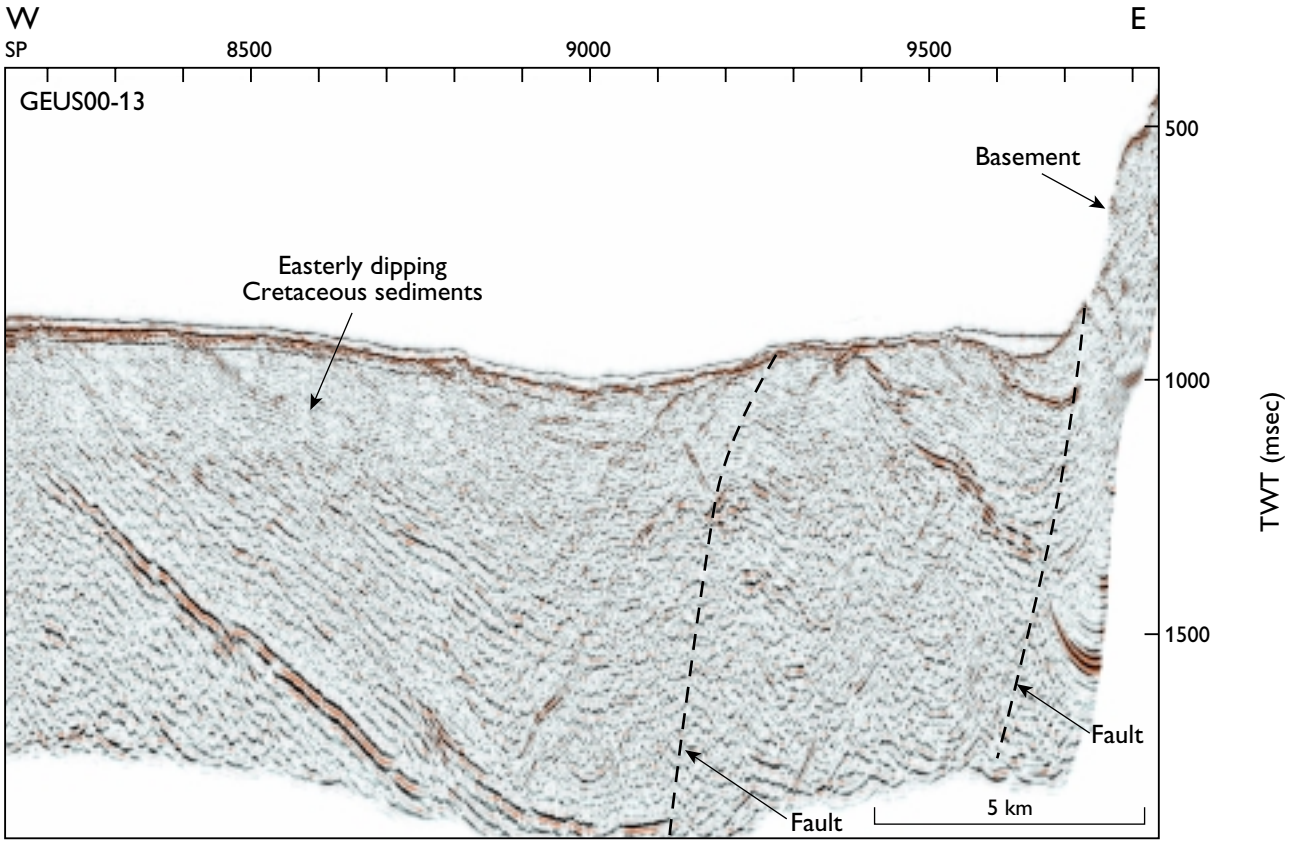

Fig. 4. Example of seismic data from Uummannaq Fjord. Part of line GEUS00-13 showing easterly dipping Cretaceous sediments in fault-blocks with Precambrian basement outcrop at the eastern end. Location shown in Fig. 1. **SP**: shot point.

packed in the inner part of the fjord around Uummannaq.

Of two long transits (GEUS00-14 and -15) across Uummannaq Fjord to the basalt area and back, the eastern end of line GEUS00-15 was terminated early because of dense concentrations of icebergs. Further acquisition of planned lines east of 52°30′W had to be abandoned because of densely packed icebergs, and thus only a few crossings over the eastern margin of the basin were made. New lines were planned in the accessible part of the fjord. After finishing work in the southern part of Uummannaq Fjord, a transit to the north between Ubekendt Ejland and Upernivik Ø (GEUS00-22 and -27) was terminated by large concentrations of icebergs at 71°27′N. It was not possible to proceed farther north, and the entire programme east of Svartenhuk Halvø in the northern part of the basin was abandoned.

Good reflections were obtained on most of the lines acquired and only few areas of moraine or large sills were noted. The area comprises fault-blocks, and good images of many of the faults were obtained (Fig. 4). Along the eastern margin of the area, several crossings from Cretaceous sediments to Precambrian basement were achieved (Fig. 4), and many images were also obtained of the margin of the basalts, as well as reflections from below the top of the basalts.

Areas west of Ubekendt Ejland and Nuussuaq where basalt is exposed at the seabed

Acquisition of lines west of Nuussuaq and Ubekendt Ejland was only a second priority. However, the favourable weather conditions made it possible to expand the acquisition programme considerably in this structurally poorly known area. Additional lines were thus acquired where basalts are found near the seabed, and water depths were large enough to achieve significant penetration of the basalts above the first seabed multiple.

Older seismic surveys in this area (GGU/1995 and Brandal/1971; Chalmers *et al.* 1999a) have shown that there are reflections from below the top basalt reflection. The significance of these reflections is, however,

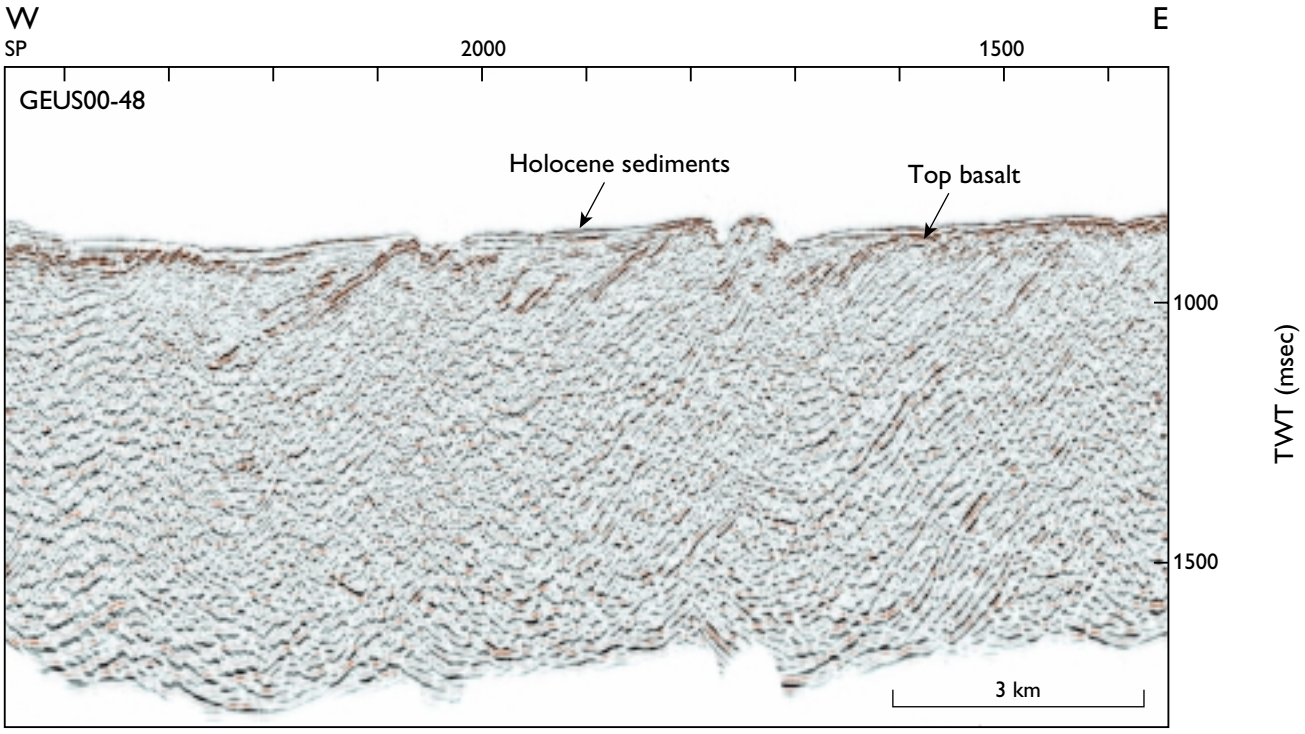

Fig. 5. Example of seismic data from the area north-west of Nuussuaq where basalts crop out at the seabed. Part of line GEUS00-48. The dipping reflections may come from syn-magmatic half-grabens or westward-dipping Cretaceous or lower Paleocene sediments (see text). Location shown in Fig. 1. **SP**: shot point.

not well understood; the different interpretations of the area so far published (Whittaker 1995, 1996; Geoffroy *et al.* 1998; Chalmers *et al.* 1999b) have substantially different implications with respect to its prospectivity. The presence of a type IV AVO (amplitude versus offset) anomaly associated with a bright spot on some of the GGU/1995 lines (Skaarup & Chalmers 1998; Skaarup *et al.* 2000) has significance from the point of view of hydrocarbon prospectivity.

Approximately 710 km of data were acquired in a broad grid extending from the mouth of Vaigat in the south to Svartenhuk Halvø in the north during a 3.5-day period. Excellent reflections were received from up to and over 500 msec below the top of the basalts in many areas (Fig. 5). Some of these sub-top basalt reflections are undoubtedly from lithological variations within the basalt sequences and preliminary correlation of the magnetic and seismic data suggests that it may be possible to develop a detailed seismic and magneto-stratigraphy. Other reflections seem to come from half-grabens (Fig. 5). While it is possible that the latter are syn-magmatic, as discussed by Geoffroy *et al.* (1998), it is also possible that they derive from westward-dipping Cretaceous or lower Paleocene sediments beneath thin basalts west of Nuussuaq. Quantitative interpretation of the magnetic data may resolve this question.

Processing

As noted above, the seismic data processing was initiated during the survey on selected lines, both to check data quality and to contribute to adjustments in the survey programme. The possibilities of removing the sea-bottom multiple were carefully tested, but although it was possible to weaken the sea-bottom multiple substantially, it was still too strong to identify primaries below the multiple except in a few places. This problem was expected because of the source strength (160 in^3 in total) and in particular the streamer length (600 m). In order to avoid problems in migration, it was therefore decided not to migrate the data below the sea-bottom multiple. The relatively time-consuming Kirchoff migration algorithm has been used to ensure a proper migration of the steeply dipping features common in the survey area. The velocity analyses show very high velocities in general, not only in areas covered by basalt, but also in the sediments below the Quaternary cover in most of the survey area, and in particular in Vaigat.

Summary

The cruise was very successful. Due to very favourable weather and ice conditions, 2743 km of good quality data were acquired, nearly 20% more than originally planned. High concentrations of icebergs prevented acquisition of data in the eastern part of Uummannaq Fjord and east of Svartenhuk Halvø.

Data from project *NuussuaqSeis 2000* have increased considerably the seismic coverage in the region, and it is anticipated that the new data will have direct implications for the evaluation of the hydrocarbon potential.

Acknowledgements

Funding for the project was provided by the Danish Energy Research Programme (ENS J.nr. 1313/99-0024) and the Bureau of Minerals and Petroleum, Government of Greenland. Captain Peter Østrin and the crew of R/V *Dana* are thanked for their professionalism and cooperation during the cruise. The splendid and untiring efforts of our two technicians, Per Trinhammer (Aarhus University) and Egon Hansen, reduced technical downtime to a minimum.

References

Bojesen-Koefoed, J.A., Christiansen, F.G., Nytoft, H.P. & Pedersen, A.K. 1999: Oil seepage onshore west Greenland: evidence of multiple source rocks and oil mixing. In: Fleet, A.J. & Boldy, S.A.R. (eds): Petroleum geology of Northwest Europe: Proceedings of the 5th Conference, 305–314. London: Geological Society.

Chalmers, J.A., Pulvertaft, T.C.R., Marcussen, C. & Pedersen, A.K. 1999a: New insight into the structure of the Nuussuaq Basin, central West Greenland. Marine and Petroleum Geology **16**(3), 197–224.

Chalmers, J.A., Whittaker, R.C., Skaarup, N., Pulvertaft, T.C.R., Geoffroy, L., Skuce, A.G., Angelier, J., Gelard, J.P., Lepvrier, C. & Olivier, P. 1999b: The coastal flexure of Disko (West Greenland), onshore expression of the 'oblique reflectors': discussion and reply. Journal of the Geological Society (London) **156**(5), 1051–1055.

Christiansen, F.G., Marcussen, C. & Chalmers, J.A. 1995: Geophysical and petroleum geological activities in the Nuussuaq – Svartenhuk Halvø area 1994: promising results for an onshore exploration potential. Rapport Grønlands Geologiske Undersøgelse **165**, 32–41.

Christiansen, F.G. *et al.* 2000: Petroleum geological activities in West Greenland in 1999. Geology of Greenland Survey Bulletin **186**, 88–96.

Geoffroy, L., Gelard, J.P., Lepvier, C. & Olivier, P. 1998: The coastal flexure of Disko (West Greenland), onshore expression of the 'oblique reflectors'. Journal of the Geological Society (London) **155**(3), 463–473.

Kuijpers, A., Lloyd, J.M., Jensen, J.B., Endler, R., Moros, M., Park, L.A., Schulz, B., Jensen, K.G. & Laier, T. 2001: Late Quaternary circulation changes and sedimentation in Disko Bugt and adjacent fjords, central West Greenland. Geology of Greenland Survey Bulletin **189**, 41–47 (this volume).

Marcussen, C., Lykke Andersen, H., Chalmers, J.A., Rasmussen, R., Trinhammer, P. & Hansen, E. 2001: Seismic acquisition in the offshore part of the Nuussuaq basin during summer 2000. Cruise report. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2001/18**, 65 pp.

Skaarup, N. & Chalmers, J.A. 1998: A possible new hydrocarbon play, offshore central West Greenland. Geology of Greenland Survey Bulletin **180**, 28–30.

Skaarup, N., Chalmers, J.A. & White, D. 2000: An AVO study of a possible new hydrocarbon play, offshore central West Greenland. AAPG Bulletin **84**(2), 174–182. Tulsa: American Association of Petroleum Geologists.

Whittaker, R.C. 1995: A preliminary assessment of the structure, basin development and petroleum potential offshore central West Greenland. Open File Series Grønlands Geologiske Undersøgelse **95/9**, 33 pp.

Whittaker, R.C. 1996: A preliminary seismic interpretation of an area with extensive Tertiary basalts offshore central West Greenland. Bulletin Grønlands Geologiske Undersøgelse **172**, 28–31.

Authors' addresses

C.M., J.A.C., R.R. & T.D.J., *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark.* E-mail: *cma@geus.dk*

H.L.A., *Geological Institute, Aarhus University, Finlandsgade 6–8, DK-8200 Aarhus N, Denmark.*