

## Full crustal seismic imaging in northeast Greenland

James W. Granath,<sup>1</sup> Richard C. Whittaker,<sup>2</sup> Vijay Singh,<sup>3</sup> Dale E. Bird<sup>3</sup> and Menno G. Dinkelman<sup>4</sup> describe new techniques used to acquire a 2D seismic acquisition programme northeast of Greenland, the results of which could lead to more optimistic assessments of the hydrocarbon potential of the area.

A new reconnaissance 2D, long-offset, deep-penetration seismic reflection programme initiated in northeast Greenland (NE GreenlandSPAN) was typical of some recent globally-distributed surveys. Acquisition parameters included a 25 m shot interval, 12.5 m group interval and maximum offset of 9000 m. The record length was 18 sec, and the data were processed to pre-stack time (PSTM) images of 16 sec and pre-stack depth (PSDM) images of 40 km record length. The first phase of data, acquired in 2009, comprised 22 profiles (Figure 1, yellow lines) covering the region from 72°15' to 77°N, and extending eastward onto oceanic crust (an example is shown in Figure 2). One profile ranges northward to cross the Greenland fracture zone near the continent-ocean transition (COT), and three profiles range southward into the Jan Mayen fracture zone. Parts of the Danmarkshavn Basin, Danmarkshavn Ridge, Thetis Basin and its Marginal High, and much of the Volcanic Province were included in the survey. An interpretation of this initial data is near completion, and a second phase of acquisition was completed in September 2010 (Figure 1, red lines). The Phase II data extends the coverage to 81.5° N across the Hovgaard Fracture Zone. A phase III is planned for 2011, primarily as infill acquisition.

### Acquisition

Rarely does seismic acquisition face the challenges present in the Arctic (Figure 3a). Earlier attempts to acquire seismic data in the area were hampered by heavy ice coverage. Consequently, new techniques were developed and employed for the first time in the survey. A proprietary streamer and deployment technology was used to acquire data below the pack ice, while an icebreaker was used to clear first-year ice for the primary acquisition vessel (Figure 3b), allowing the seismic programme to remain focused on geophysical operations.

In this survey, a simple 2D acquisition package was used consisting of a single 8000 m streamer and a single 4330 in<sup>3</sup> source. There was no tail buoy, and no front end position-

ing data were acquired. The streamer cable contained 640 channels over 40 active seismic modules and 80 active 100 m streamer sections (one forward and one aft section per module). The system was configured with 16 auxiliary channels for the monitoring of gun string hydrophones.

Due to the unique towing configuration and to the intention to tow the equipment below ice, the vessel incorporated an additional short 'sacrificial' lead-in and a ruggedized boot adaptor to minimize the replacement cost of valuable 'at risk' equipment near the gun array. Throughout the operation, the airgun source array was fired every 50 m. At each shot point, 18 seconds of seismic reflection data were sampled at a 2 millisecond interval, and recorded to tape. A total of 5283 full fold line km were acquired with less than 3% technical downtime.

### Processing

The geophysical objectives were achieved by defining image requirements and then working backwards through the seismic workflow to select the appropriate mix of processing applications. Following is a simplified processing flow:

Pre-processing:

- Geometry merge and QC
- Signal processing
- Velocity analysis
- Noise attenuation
- Multiple attenuation
- Signal enhancement

Pre-stack depth migration:

- Model building
- Integrating ancillary data – well, gravity, magnetics
- Migration

Post-processing:

- Multiple attenuation
- Mute/Stack/TVF/Gain
- SEG Y

<sup>1</sup> Consultant to ION GX Technology, Highlands Ranch, Colorado.

<sup>2</sup> GeoArctic, Calgary, Alberta.

<sup>3</sup> Bird Geophysical, Houston, Texas.

<sup>4</sup> ION GX Technology, Houston, Texas.

\* Corresponding author, E-mail: menno.dinkelman@iongeo.com

# Petroleum Geology & Basins

Due to the unique problems and issues during acquisition in icy conditions, new processing techniques were designed and implemented. Acquisition under ice requires a modified signal processing and de-signature approach. In the case of this survey, optimum noise attenuation was accomplished using a cascaded processing flow approach which eliminated noise from various sources. Larner noise and noise gener-

ated by ice-breaking required new tools. Similarly, multiple attenuation in Arctic data also requires a cascaded-flow approach where the method and sequencing have to be just right for optimum results. Owing to the limitation that 2D migration algorithms assume data reside in a single 2D plane, overcoming the noise and multiple problems for 2D Arctic data is often more challenging than for a typical 3D.

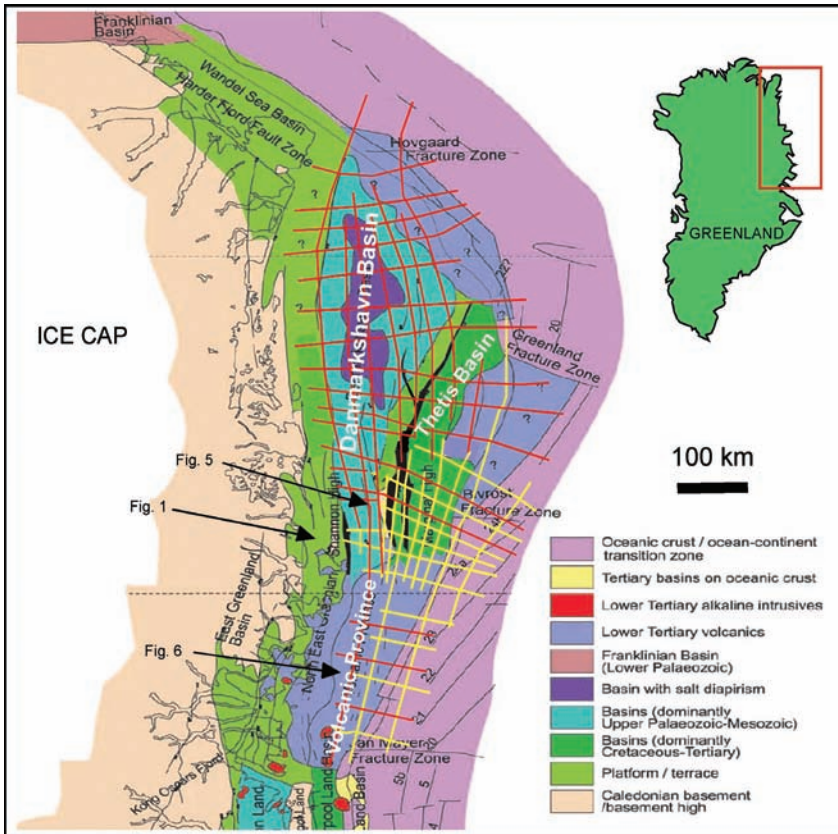


Figure 1 Tectonic elements in NE Greenland with the location of the Phase I (yellow) and planned Phase II (red) NE Greenland SPAN seismic programmes (after Hamman et al., 2005).

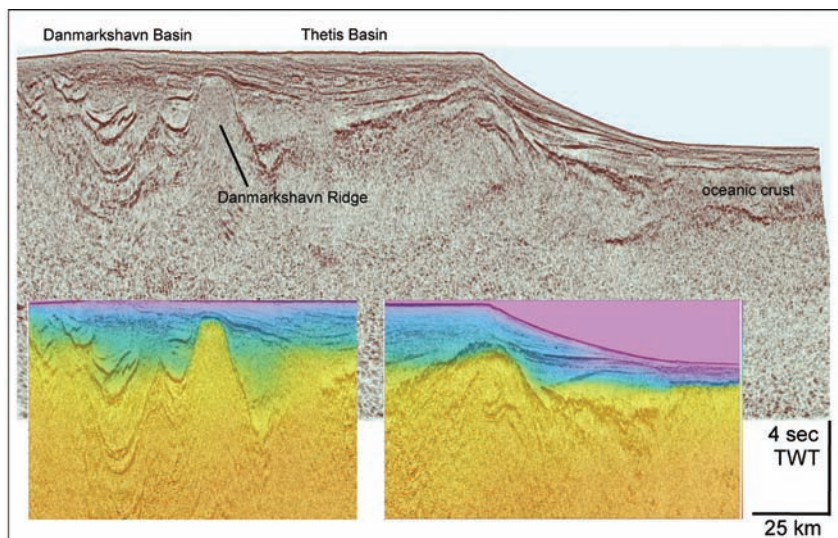


Figure 2 Example PSTM across Danmarkshavn and Thetis Basins, full 40 km amplitude display, with corresponding PSDM segments overlaid by the PSTM velocity field.

### Potential field modelling

Modelling of gravity and magnetic data is an important component of the processing workflow. Potential field interpretations are used to constrain the seismic velocity for the deep crustal structural imaging and interpretation. These studies are incorporated twice in the processing/interpretation workflow, first during PSDM processing to sharpen imaging of deep intra-basement structures and second during a crustal-scale interpretation of basement and its sedimentary cover.

The initial components of these 2D models are high resolution gravity and magnetic data acquired along the survey lines themselves and refraction-derived sedimentary and crustal horizons from the CRUST 2.0 global model (Mooney et al. 1998). Other sources of control such as wells and information from published sources are used. The first phase of modelling focuses on understanding the geometry of intra-crystalline crustal horizons and Moho to assist seismic processors with an understanding of sub-basement velocity structure.

The second phase of gravity modelling is focused on supra-basement features and variations in lithology that have an effect on the velocity structure, such as salt nappes, carbonate buildups, or volcanic edifices. Guiding principles in modelling are: 1) hold densities constant for layers throughout the study area, 2) proportion magnetic anomaly wavelengths to their source depths, and, most importantly 3) tie models to seismic refraction data, which independently fix the depths to basement and Moho.

### Geology

The main geoscience objective of the survey was to provide a better understanding of the basin architecture at the crustal scale and the petroleum systems in the offshore areas ranging from Northeast Greenland Volcanic Province north to the Danmarkshavn Salt Basin to and eastward into the Thetis Basin (Figure 1).

The Northeast Greenland Shelf was the focus of the Phase I programme. Caledonian crystalline basement is widely exposed onshore to the west of the survey, and locally-preserved sections of Carboniferous to Jurassic sedimentary rocks are present. A thick section of Palaeozoic through Cretaceous sedimentary rocks is interpreted in the

nearshore platformal area (Hamman et al., 2005), thickening offshore in the Danmarkshavn Basin where it is overlain by a complete Cenozoic section (Figure 4). Recurrent faulting has controlled the post-Caledonian sedimentation, which also appears to have been reactivated during opening of the Atlantic. Only the southernmost part of the Danmarkshavn Basin was imaged in Phase I (Figure 1). No salt features were captured in the seismic data.

The PSDM seismic data have provided new information on the extent and thickness of Mesozoic sediments in the Thetis Basin. Middle Jurassic rifting opened the Thetis Basin to the east of the Danmarkshavn Ridge that contains a thick Cretaceous and younger section (Hamman et al., 2005). It also appears to contain an older platformal section equivalent to areas to the west (Figure 4). This deeper part of the Thetis Basin was inferred from a deeper magnetic basement (Haimilia et al., 1990) and gravity modelling associated with previous more conventional seismic surveys (Hamann et al., 2005). There is clear evidence for the presence of a thick section below the base Cretaceous unconformity in the Thetis Basin and for its subcrop along the Danmarkshavn Ridge (Figure 5), suggesting that rich oil-prone Jurassic source rocks are likely present in this outer Greenland shelf area.

To the south of the NE Greenland Shelf, the survey imaged much of the outboard half of the East Greenland Volcanic Province, a region dominated by Tertiary flood basalts, and its bordering oceanic crust (Figure 6). The southern extent of the Danmarkshavn Basin quite clearly underlies the northern part of the Volcanic Province in the data set, where Palaeozoic through Cretaceous rocks can be mapped beneath the edge of volcanic cover.

The NE Greenland Shelf is the conjugate margin to the Lofoten and Vøring Margins of Mid-Norway and it lay southwest of the Barents Shelf prior to North Atlantic Continental break up. The survey imaged intra- and sub-basalt reflectors in the volcanic province and on the volcanic margin where seaward dipping reflectors (SDRs) are interpreted (Figures 5 and 6). Several of the lines cross the Continent Ocean Transition (COT) which is topped by well developed SDRs and extend out over ocean crust where deep reflectors near 10 km are interpreted as the Moho. These deep reflectors dip west towards the East



Figure 3 Ice conditions during acquisition – 3a: June 2010 coverage, 3b: September 2010 coverage. Note icebreaker leads the acquisition ship to clear a path through first-year ice.

# Petroleum Geology & Basins

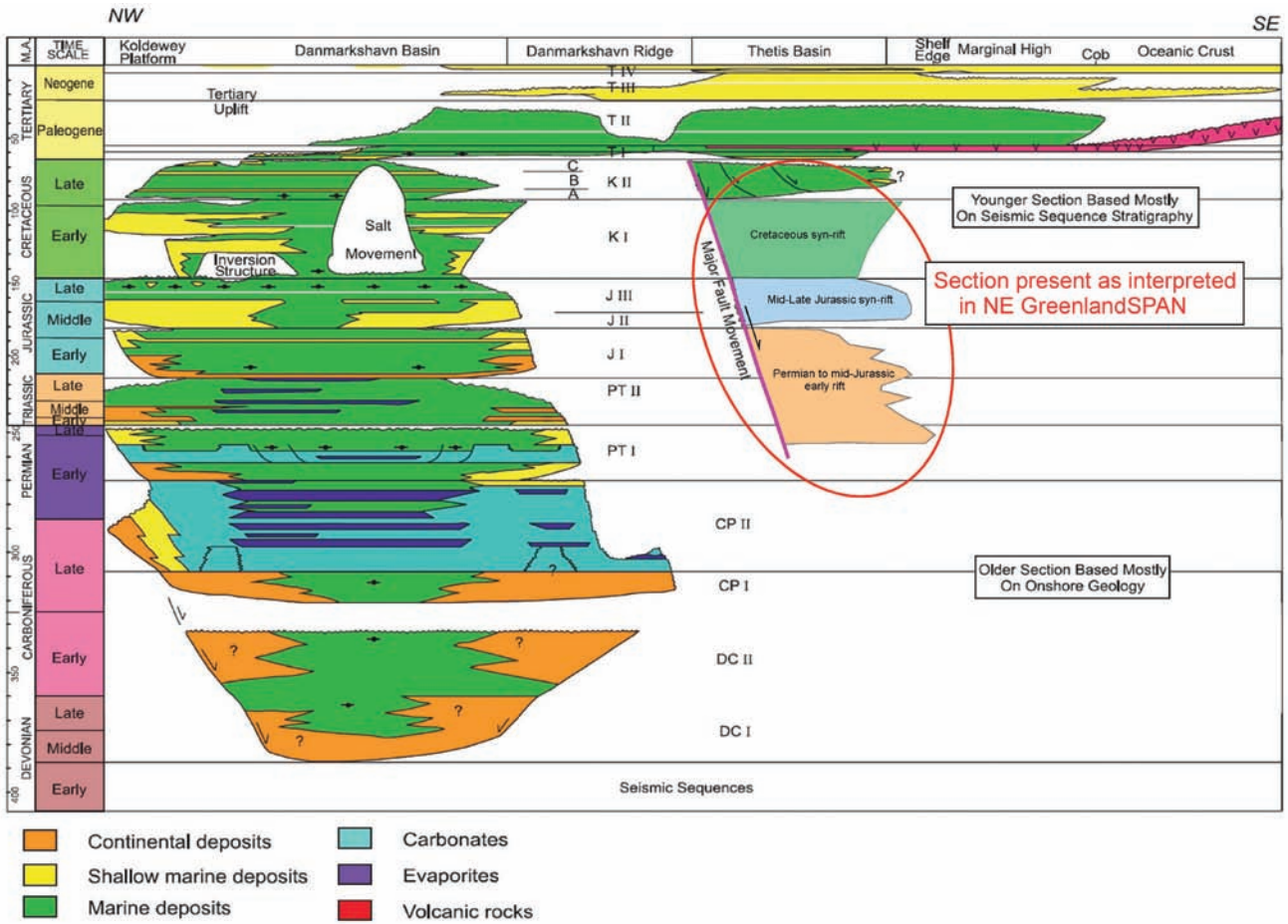


Figure 4 Stratigraphic architecture of the NE Greenland shelf, with modification as implied by the interpretation of the new data set (after Hamann et al., 2005).

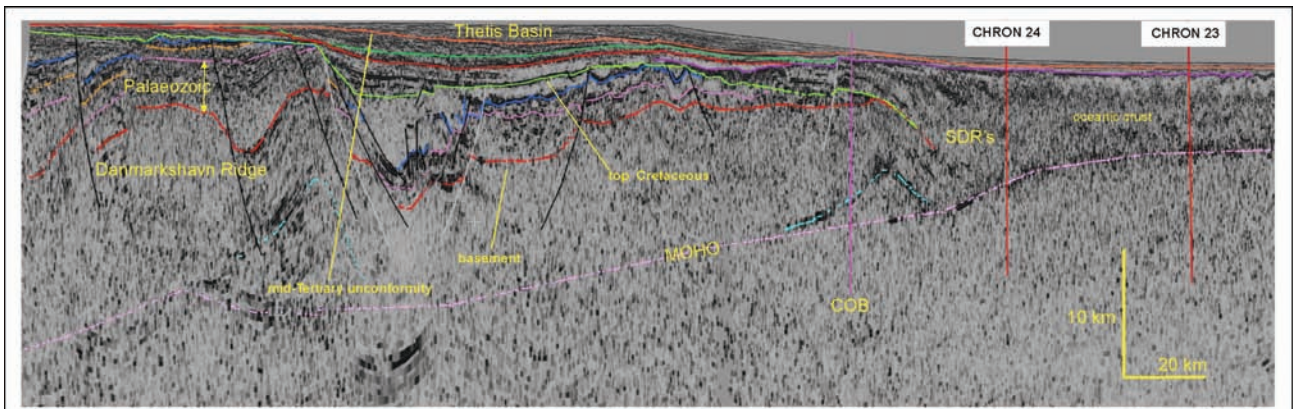


Figure 5 Representative full crustal seismic profile across the NE Greenland Shelf illustrating the relationships of the Danmarkshavn Basin and Ridge, the Thetis Basin, and oceanic crust, shown in average energy display. Of particular note is the thickness of the stratigraphic sections and the interpreted presence of an early and pre-Mesozoic stratigraphic section in the Thetis Basin.

Greenland continental crust to a depth of about 22–25 km at the west end of the seismic lines. A high-amplitude deep crustal reflector is evident at about 15 km along the outer margin (Figure 5), which is possibly related to a lower crustal reflector described on the Norwegian margin, where it has been attributed to crustal underplating.

North Atlantic sea floor spreading began in the Paleogene in NE Greenland, and locally it is marked by Chron 24 at the beginning of Eocene time. These new data provide strong evidence for a COT closer to the Greenland coastline in the NE Greenland Volcanic Province than many earlier interpretations, similar to the predictions by

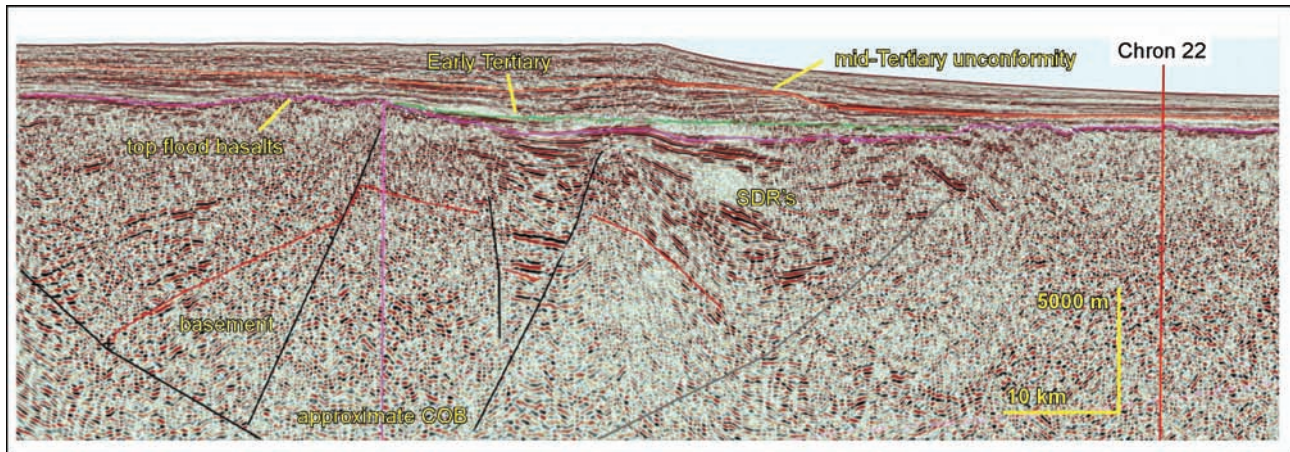


Figure 6 Uppermost 15 km of a profile across the Volcanic Province from the Phase I survey.

Scott and Whitham (2000). This new interpretation has an impact on the break-up history of both the Greenland and conjugate Norwegian margin, north of the Jan Mayen Fracture Zone, likely resulting in a revised plate tectonic model of the North Atlantic.

### Exploration implications

The Phase I survey covered the Danmarkshavn Basin, the Thetis Basin, and the Northeast Greenland Volcanic Province, an area collectively to be estimated US Geological Survey to contain over 31 billion barrels of oil equivalent. Exhumed oil deposits in the Traill Ø area (Price and Whitham, 1997), just to the southwest of the Phase I survey, indicate that a viable petroleum system was indeed active in the region.

The new data set shows a thick sedimentary sequence (> 9 km) in the southern part of the Danmarkshavn and Thetis Basins. Both basins are interpreted to include a thick Mesozoic section, as well as older Palaeozoic sediments that are thought to subcrop along the Danmarkshavn Ridge. Extensive syn-rift faulting is interpreted along the eastern and western margins of the Danmarkshavn Ridge, and large scale folding and doming have affected the area since break-up, leading to the development of a rich variety of potentially large hydrocarbon traps.

### Conclusions

The NE GreenlandSPAN discussed here is a new phase of seismic acquisition in ice-hampered regions and may influence petroleum operations in NE Greenland. Some of the techniques can be applied to focused 3D acquisition. A better understanding of the opening history of the North Atlantic and reconstruction of Greenland with its conjugate Mid-Norway and Barents Sea margins must be reconciled with observations gained from the new data, such as larger extension in the NE Greenland shelf than in the Volcanic

Province, and a closer fit of the European side with the Volcanic Province north of the Jan Mayen fracture zone. The better structural development of the region can be used to develop palaeogeographic interpretations that can be used to predict source and reservoir deposits.

The seismic data have resulted in the identification of play types, and numerous structural leads have been mapped. Regional basin analogues and fresh interpretations suggest that rich oil-prone Jurassic source rocks are present over much of the area. These observations together with comparisons with the conjugate Mid-Norway margin suggest that the area has excellent hydrocarbon potential.

Note: The NE GreenlandSPAN surveys are carried out by ION Geophysical as part of its worldwide BasinSPAN programme ([http://www.iongeo.com/Data\\_Libraries/Spans/](http://www.iongeo.com/Data_Libraries/Spans/)).

### References

- Hamann, N. E., Whittaker, R. C. and Stemmerik, L. [2005] Geological development of the Northeast Greenland Shelf. In: Doré, A. G., and Vining, B. A. (Eds) *Petroleum Geology: North-West Europe and Global Perspectives: Proceedings of the 6<sup>th</sup> Petroleum Geology Conference*. Geological Society, London, 887–902.
- Haimilia, N.E., Hirsner, C.E., Nasichuck, W.W., Ulmichek, G. and Procter, R.M. [1990] Sedimentary basins and petroleum resource potential of the Arctic Ocean region. In: Trantz, A., Johnson, L. and Sweeney, J. F. (Eds) *The Arctic Ocean Region: Boulder, Colorado*, Geological Society of America. *The Geology of North America*, L, 503–538.
- Mooney, W.D., Laske, G. and Masters, G.T. [1998] CRUST 5.1; a global crustal model at 5 degrees X 5 degrees. *Jour. Geophys. Res.*, **103**, 727–747.
- Price, S.P. and Whitham, A.G. [1997] Exhumed hydrocarbon traps in East Greenland: analogs for the Lower-Middle Jurassic play or Northwest Europe. *AAPG Bulletin*, **81**, 196–221.
- Scott, R.A. and Whitham, A.G. [2000] East Greenland geology plays role in Northwest Europe margin. *Offshore*, **60**, 145, 150, 184.