2018 EAGE ANNUAL
80TH CONFERENCE + EXHIBITION
COPENHAGEN | DENMARK

# Detailed structure of buried glacial landforms revealed by high-resolution 3D seismic data in the SW Barents Sea

Benjamin Bellwald[1], Sverre Planke[1,2], Stéphane Polteau[1], Nina Lebedova-Ivanova[1], Amer Hafeez[1], Jan Inge Faleide[2], Reidun Myklebust[3]

[1]Volcanic Basin Petroleum Research (VBPR) AS, Oslo Science Park, Gaustadalléen 21, N-0349 Oslo, [2]Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Sem Sælands vei 1, N-0371 Oslo, Norway, [3]TGS, Lensmannslia 4, N-1386 Asker

Glacial landforms identified in seismic 3D and multibeam data of the Barents Sea have improved the knowledge about past glaciations and associated geohazards. High-resolution P-Cable 3D seismic data were acquired in this area with an inline separation of 6 m, a source frequency range of 5-350 Hz and an source-receiver offset range of 120-160 m. Seabed images derived from the P-Cable data show an increased resolution and sharpness compared to images from conventional 3D seismic and multibeam echosounder data. High-resolution images of the buried Upper Regional Unconformity (URU) were derived from the P-Cable data, revealing previously un-recognized structures such as hill-hole pairs and rhombohedral and transverse ridges. These observations indicate different subglacial thermal regimes, the presence of permafrost, and a strong link with variations in the underlying geology. No reflections are imaged within the interglacial sediment package in the conventional seismic data. However, reflections interpreted as the top of a shear margin moraine, shear planes, mass transport deposits, and soft beds are visible in the P-Cable data. Meter-scale glacial landforms and layers identified in the P-Cable cubes comprise new information about glacier dynamics, fluid flow, and faults, which are valuable for geotechnical and geohazard evaluations of offshore infrastructure.

**Extended Abstract submitted to EAGE, in review**

## Introduction

Glacial deposits may influence fluid flow and geotechnical soil properties of previously glaciated continental shelves. Large ice streams and disintegrating icebergs eroded the shallow sub-surface of Arctic shelves, and leave typical glacial landforms at the seabed. Additional to the seabed, landforms evidencing past glaciations are found within glacial sediment packages, along glacial unconformities, and in underlying glacio-tectonically deformed strata. These landforms are imaged and characterized using multibeam echosounders, 3D seismic data, shallow cores, and borehole data.

This study is based on four high-resolution P-Cable 3D seismic cubes from different areas of the SW Barents Sea, where the Barents Sea Ice Stream and disintegrating icebergs eroded Lower Cretaceous bedrock during multiple Pleistocene oscillations (Fig. 1) (Piasecka et al., 2016). These eroded Cretaceous sediments were redeposited in the Bjørnøyrenna and the Bear Island Trough Mouth Fan (Fig. 1a). The successive glacial advances and retreats bulldozed and deformed the underlying bedrock, and led to the formation of the Upper Regional Unconformity (URU) and a multitude of glacial landforms.

The Barents Sea currently attracts large interest of the petroleum industry, as gas and oil occur here in shallow reservoirs. An improved knowledge about the shallow geology in this area is important to ensure safe operations and monitoring of the environmental impact of activities offshore. In this contribution, we show that high-resolution 3D seismic data can help companies identify geological landforms, beds, faults, and geohazards related to the shallow subsurface, and make the drilling operations safer for the environment. Another advantage of this unique technique is its unrevealed imaging capability that can resolve horizons within glacial packages in multibeam quality, and hence can help constrain ice-sheet dynamics and the effect of inherited structures. We study i) the inherited effect of faults in the shallow subsurface and ii) the external effect of eroding ice masses on landforms identified along different glacial horizons.

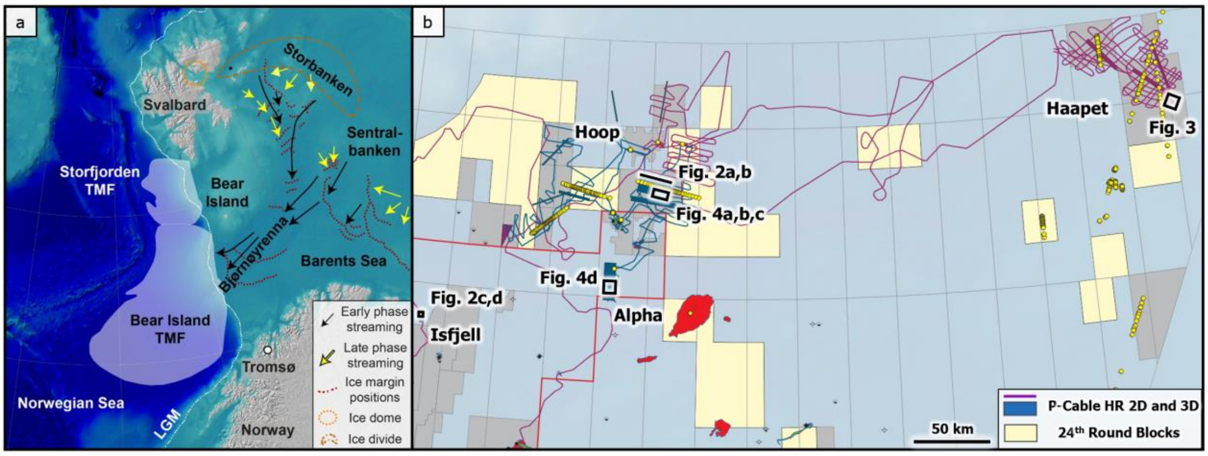


***Figure 1. a)*** *Bathymetric map of the SW Barents Sea with major glacial landforms and ice flow directions. TMF: Trough mouth fan.* ***b)*** *Study area with P-Cable datasets and petroleum discoveries (red).*

## Methodology and Technology

The P-Cable data were acquired with an inline separation of 6 m, an offset range of 120-160 m for all receivers, and a 300 in$^3$ air-gun array. The P-Cable data have smaller bin sizes (c. 3-6 m) as well as an increased horizontal and vertical resolution compared to conventional seismic data (Tab. 1, Fig. 2). Seabed images interpreted in P-Cable 3D seismic data show an increased resolution and sharpness compared to surfaces derived from multibeam echosounder and conventional 3D seismic data (Figs. 2c, 2d). The seismic cubes used in this study have bin sizes of 6.25 x 4.75 m and a frequency of up to 350 Hz in the uppermost 100 m. The shallower subsurface can thus be imaged with a vertical resolution of 1-5 m and a bin-size horizontal resolution of 3-6 m, which is up to five times higher than in conventional seismic data. The glacial landform assemblages are interpreted from time-structure maps of the seabed and the URU, which are the main shallow seismic horizons in the area and represent the boundaries of the glacial sedimentary package. Additional to the time-structure maps, amplitude information and isopach maps are used to characterize glacio-erosive processes (Fig. 3).

***Table 1.*** *P-Cable and conventional 3D seismic acquisition parameters for surveys of the SW Barents Sea. CMP: Common midpoint.*

| | **P-Cable 3D 2014** | **Conventional 3D** |
|---|---|---|
| **Streamer spread** | 16 x 9.5 m x 25 m | 8 x 100 m x 6000 m |
| **Number of channels** | 8 x 16 = 128 | 480 x 8 = 3840 |
| **Offset range of all streamers** | 122-163 m | 178-6180 m |
| **Dominant source frequency** | c. 145 Hz | 50-70 Hz |
| **Bin size** | 6.25 m x 4.75 m | 25.00 m x 6.25 m |

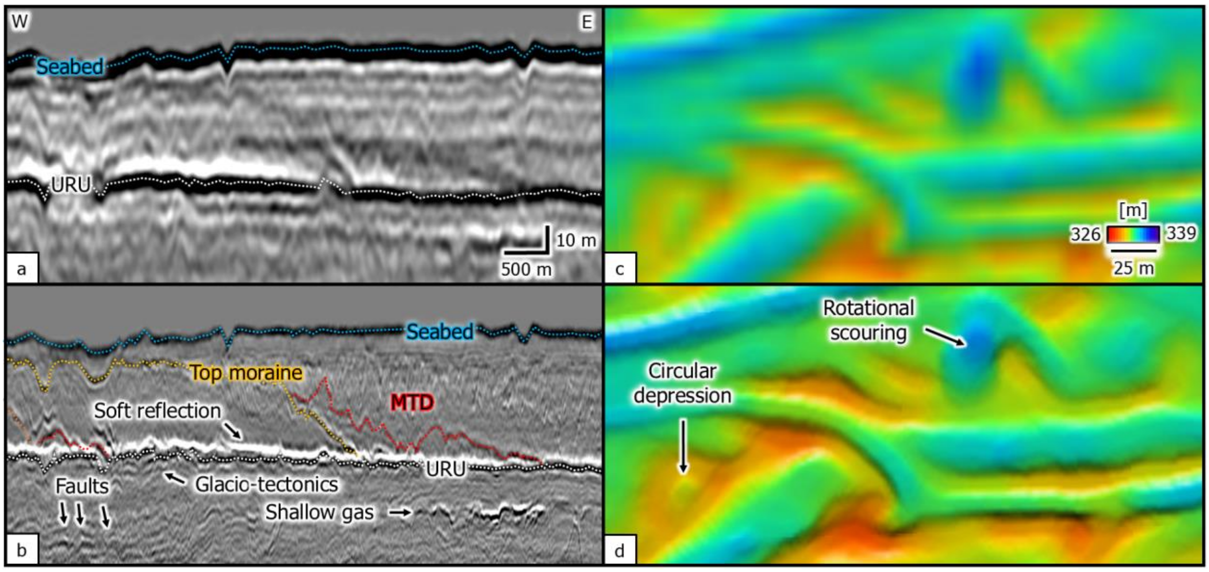


***Figure 2. a)*** *Comparison of vertical resolution of seismic data collected by conventional 3D seismic and* ***b)*** *P-Cable 3D seismic in the Hoop area.* ***c)*** *Comparison of horizontal resolution of the seabed reflection collected by conventional multibeam echosounder (Kongsberg EM300, 30 kHz) and* ***d)*** *P-Cable 3D seismic in the Isfjell area. Data courtesy of TGS, WGP, UiT, and VBPR.*

## Seabed

The seabed of the SW Barents Sea is characterized by different sets of mega-scale glacial lineations, iceberg ploughmarks and pockmarks (Fig. 3a) (e.g. Piasecka et al., 2016; Andreassen et al., 2017). Comparisons with seabed images generated by conventional 3D seismic data and conventional multibeam echosounder data show that the P-Cable technology resolves the seabed in similar or higher quality. P-Cable 3D can vertically resolve seabed landforms in 1-5 m, and have an increased sharpness compared to grids derived from conventional multibeam echosounder images (Fig. 2c, 2d). Thus, the P-Cable data can identify geological processes that are active on a meter-scale, such as ploughmarks indicating iceberg rotation (Fig. 2d). Amplitude information of the seismic data allows determining the nature of the seabed (Fig. 3b). Chaotically reworked sediments forming the rims of iceberg ploughmarks are correlating with the lowest peak seismic amplitudes. In locations where the icebergs eroded into bedrock, the seabed is instead characterized by the highest peak seismic amplitudes. Isopach maps of the glacial package can be used to map areas where Cretaceous bedrock is outcropping at the seabed (Fig. 3c).

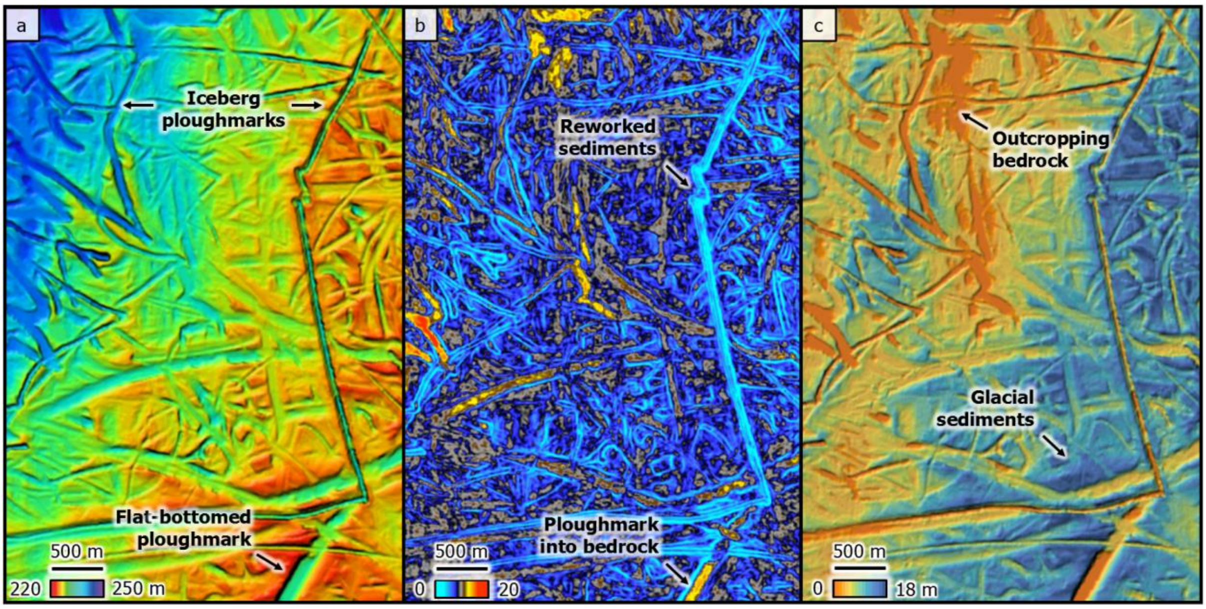


***Figure 3.*** *Seabed of the Haapet Dome imaged by P-Cable 3D seismic data.* ***a)*** *Structure map.* ***b)*** *Peak seismic amplitude of the seabed.* ***c)*** *Isopach map of the glacial package. Data courtesy of TGS, WGP, and VBPR.*

**Buried Horizons**

Conventional seismic data show that the URU landform assemblage is dominated by mega-scale glacial lineations (Piasecka et al., 2016). An increased frequency of c. 300 Hz at URU depths in P-Cable data allows to image geological structures with a resolution of 1-6 m along this horizon. Additional landforms identified in P-Cable 3D seismic data include iceberg ploughmarks, rhombohedral ridges, transverse ridges, and hill-hole pairs (Fig. 4). Reflections within the glacial package, not visible in conventional seismic data, include the top of a shear margin moraine, shear planes, mass transport deposits and soft beds (Fig. 2b) (Bellwald and Planke, 2018). Mass transport deposits onlapping the flanks and iceberg ploughmarks at the top of the moraine indicate that the moraine has been degraded by ongoing slope failure and iceberg ploughing.

Rhombohedral and transverse ridges are associated with underlying polygonal faults and indicators of geological structures formed by subglacial thermokarstic processes (Fig. 4a-c). Therefore we interpret these features to indicate permafrost, gas hydrates, and potentially shallow gas in their subsurface.

Hill-hole pairs are glaciotectonic features formed by rafting of subglacial hydrate-bearing sediment and shallow bedrock, and imply a grounded Barents Sea Ice Stream freezing at its bed. The hill has been deposited on the lee-side of the ice-streaming direction (Fig. 4d). P-Cable data indicate that the occurrence of hill-hole pairs is associated with shallow faults. As faults are supposed to be locations of increased fluid flow, gas hydrate formation could be promoted there and favor freeze on of grounded ice streams.

**Conclusions**

This study shows that high-resolution seismic data can be used to identify and map geological structures in multibeam echosounder quality of both the seabed and the shallow subsurface. New observations, including thermokarst landscapes, hill-hole pairs, soft beds and a shear margin moraine have led to the development of a revised ice-stream model of the SW Barents Sea. P-Cable data show that glacial expressions are formed by processes related to glaciation and deglaciation, and that the geometry and location of some of these expressions are defined by deeper faults.

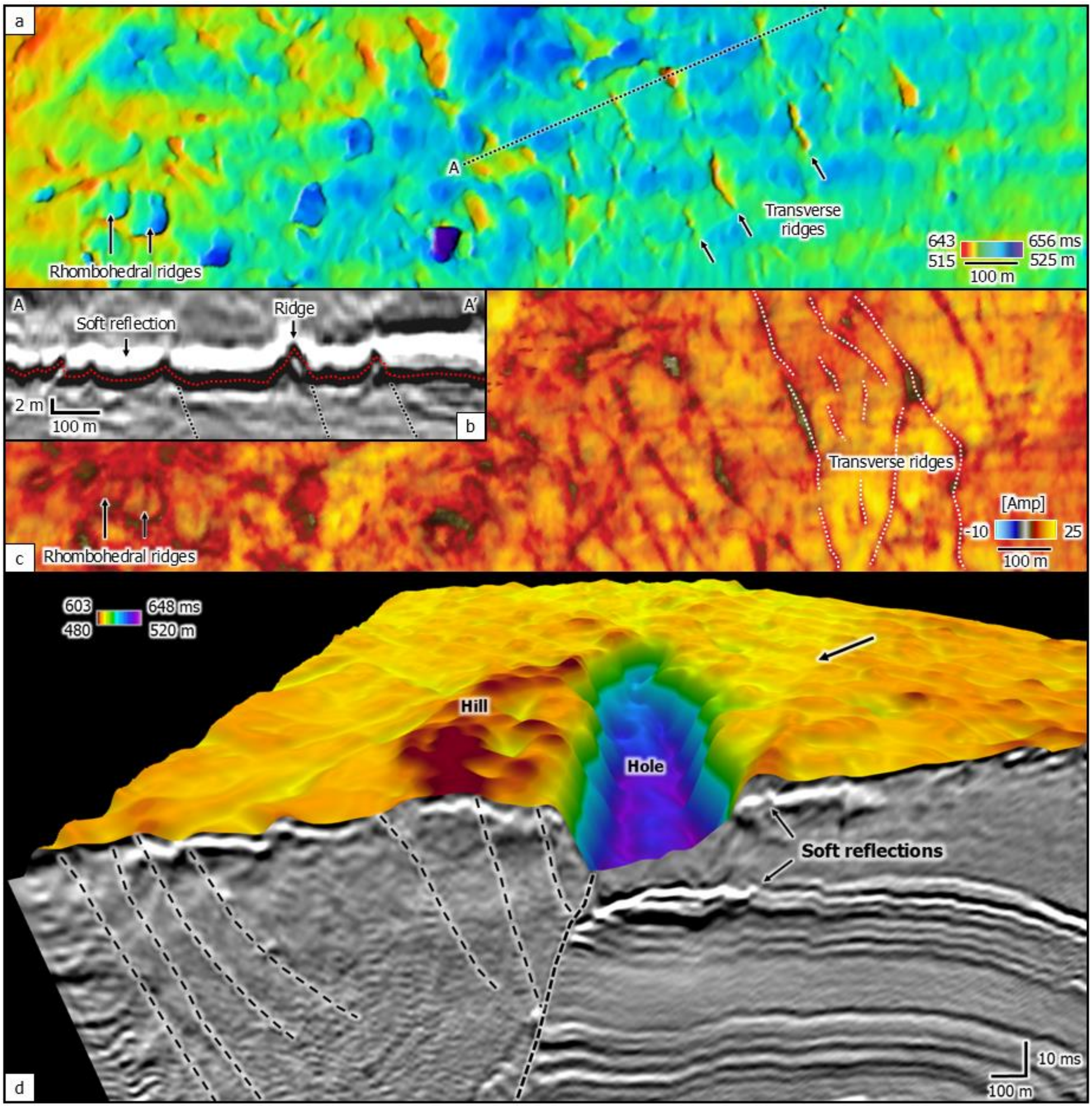


***Figure 4.*** *Thermokarst landscape at URU of the Hoop area based on P-Cable 3D seismic data.* ***a)*** *Structure map.* ***b)*** *Seismic profile across transverse ridges.* ***c)*** *Peak seismic amplitude of URU. Note that the segments of individual transverse ridges can be better linked using attribute analysis.* ***d)*** *Hill-hole pair at URU imaged by P-Cable 3D seismic data of the Alpha area. The location of the hill-hole pair is linked to a deep fault, and soft reflections below. Arrow indicates ice-flow direction. Data courtesy of TGS, WGP, and VBPR.*

## References

Andreassen, K., Hubbard, A., Winsborrow, M.C.M., Patton, H., Vadakkepuliyambatta, S., Plaza-Faverola, A., Gudlaugsson, E., Serov, P., Deryabin, A., Mattingsdal, R., Mienert, J. and Bünz, S. [2017] Massive blow-out craters formed by hydrate-controlled methane expulsion from the Arctic seafloor. Science, **356**, 948-953.

Bellwald, B. and Planke, S. [2018] Shear margin moraine, mass transport deposits, and soft beds revealed by high-resolution P-Cable 3D seismic data in the Hoop Area, Barents Sea. *Special publication, Geological Society of London*.

Piasecka, E.D., Winsborrow, M.C.M., Andreassen, K. and Stokes, C.R. [2016] Reconstructing the retreat dynamics of the Bjørnøyrenna Ice Stream based on new 3D seismic data from the central Barents Sea. *Quaternary Science Reviews*, **151**, 212-227.