Seismic profiling on Arctic glaciers

Tor Arne Johansen,[1*] Bent Ole Ruud,[1] Nils Erik Bakke,[2] Per Riste,[2] Erik P. Johannessen[2] and Tormod Henningsen[2] **describe the operational challenges involved in acquiring good quality seismic data on ice or snow covered surfaces of the Arctic. The imaging results are reported separately in the Technical Article on p. 35.**

Investigating for the structure of the upper crust in polar areas is challenging, first and foremost due to the low temperature, harsh weather conditions, and ice dynamics. Furthermore, since these regions are environmentally vulnerable, several precautions during data acquisition have to be undertaken in order to leave them in the same condition as when entered (see Trupp et al., 2009 for a brief review). The seismic method is in principle non-destructive to the environment and it provides the main source of information for revealing the geological structures below the earth's surface. As details of the upper crust are important for understanding the development and dynamics of the earth, so they are for the cause of exploration for hydrocarbons and sequestration of carbon dioxide. According to Gautier et al. (2009) close to one-third of the world's undiscovered gas and more than one-tenth of the undiscovered oil reserves are assumed to be hidden in the subsurface north of the Arctic Circle.

Marine seismic acquisition using towed streamers is, however, extremely difficult to handle within or close to sea ice; also, the high level of ambient noise due to the ice dynamics has a severe impact on the quality of the data. Seismic acquisition on top of ice and snow covered land is from an operational point of view much easier to handle. Geophones may be hard to deploy properly on loose snow and ice compared to unfrozen sediments. However, the use of so-called snowstreamers, as seen in Figure 1, consisting of gimballed vertical geophones attached to a cable including the lead-in, and towed behind a belted vehicle, has proven to be operational effective and provides seismic data of good quality (Eiken et al. 1989).

During March and April of 2009, the University of Bergen and Statoil, in conjunction with the University Centre on Svalbard (UNIS) and Bergen Oilfield Services (BOS), conducted a 2D seismic profiling campaign, including several transects on glaciers at Nathorst Land in the Norwegian Arctic, located at the southern central part of Spitsbergen and facing the Van Mijenfjorden to the north and the Van Keulenfjorden to the south (Figure 2). The field team consisted of both professionals (BOS) and UNIS students following a course in polar seismic exploration. During the two weeks long field campaign, six seismic lines (Figure 2) comprising close to 50 km were acquired in air temperatures ranging from -10 – 40°C and at elevations between 125 and 750 m above the sea level. The main scope of the campaign was to detect geometries of the shallower sedimentary structures (e.g., clinoforms), and link them to a stratigraphic model obtained from several years of geological fieldwork within the surrounding naked mountain sides (Johannessen and Steel, 2005). In addition, two of the seismic lines were crossing a scientific well completed during the summer of 2008 (Johannessen et al., 2011).

Figure 1 Deploying the 1500 m long snow streamer with of 60 geophone groups (main picture). The streamer was towed by a band wagon which also contained the recording unit (small picture).

Proper analysis of seismic data acquired in polar environments usually requires careful processing in order to reveal the seismic signatures caused by the highly varying physical conditions of the upper few hundred metres of the crust. These are due to variations in the horizontal and vertical extent of both the permanently frozen ground (permafrost) and the glaciers, which strongly influence the seismic velocity distribution and seismic wave propagation in the shallower part of the profiles. In particular, the freezing of partly or fully water-saturated sediment increases severely its elasticity parameters and seismic velocities (Zimmerman and King, 1986, Jacoby et al., 1996, and Johansen et al., 2003). In seismic processing the effects of heterogeneous permafrost conditions are

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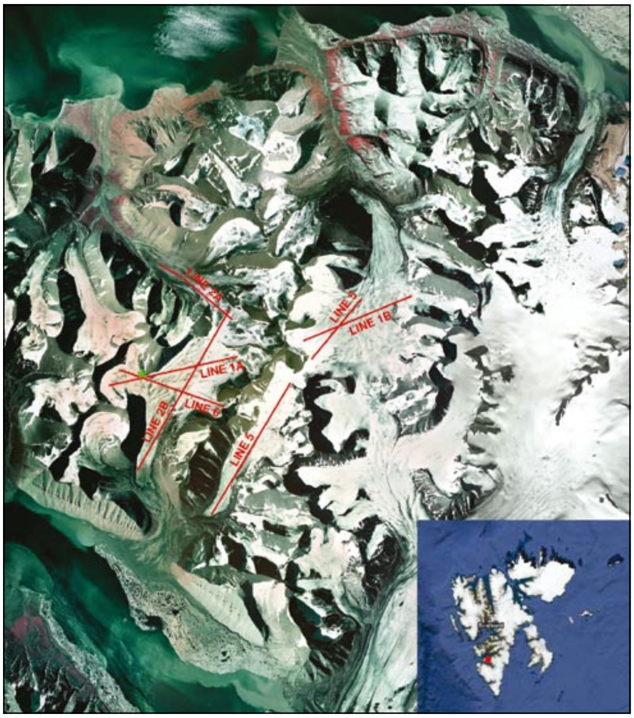

Figure 2 The study area involved the glaciers at Nathorst Land, Spitsbergen (small picture within the large picture below). Mosaic of air photos of the study area with the seismic profile lines and well position indicated.

handled by employing static corrections as shown by Trupp et al. (2009). The impact of a glacier on the seismic data is manifold; its thickness, which may vary from a few metres to several hundred metres, causes the appearance of the surface waves and the internal reverberation patterns (multiples) to vary considerably. Heterogeneities within the glacier as fractures and cavities may also generate distorting wave phenomena but, even more important, put at risk the crew conducting the field operation. The purpose of this article is to give a brief review of our experiment with focus on the main impact of the glacier conditions on the seismic data, but also on the data acquisition procedures.

Data acquisition

In the study area at Nathorst Land, the glaciers may be several kilometres long, and some few hundred metres thick. The vertical extent of the permanently frozen ground of the nearby regions uncovered by ice may be hundreds of metres, depending on the elevation and the distance to the warmer sea water. At the front end of some glaciers, the appearance of ponds of water from melted ice reveals that the temperature at the bottom of the glaciers is somewhere above the freezing point. Thus, the vertical extent of the permanently frozen ground may be less beneath glaciers than on the nearby tundra. While ice dynamics may cause large fractures to evolve, melting water may produce crevasses and tunnel systems within the ice.

Processing workflow	
1)	Trace editing
2)	Mute air wave and later arrivals
3)	Velocity filtering (fk) to remove surface- and S-waves
4)	High resolution de-aliased noise attenuation in tau-p domain
5)	Amplitude recovery
6)	Front mute
7)	Surface consistent deconvolution
8)	PSDM from surface topography

***Table 1** Processing workflow: The fk-filter was used to remove surface waves and S-waves which tend to have most of their energy at low frequencies. For the higher frequency P-wave scattering (including multiples within the glacier) a high resolution filter designed to remove linear noise proved more efficient.*

As a safety measure, the ice conditions along the planned seismic lines were monitored using geo-radar (Malå ProEX system) and, subsequently, manually inspected by teams of 2–3 persons. A safety zone of 20 m was defined transverse to, and on each side of, the profile lines. As the geo-radar provides information about the weak, potentially hazardous, zones within the ice, it also provides the thickness and shape of the glacier (Figure 6).

The weather conditions may in this environment change extremely rapidly, and within a few minutes wind and snow may cause a complete loss of visibility. Keeping tracks densely marked with sticks leading to a heated campus were always given high priority during the field operation. The balance between acceptable seismic data quality and demand for progress with the field work was kept by using an empirical maximum tolerated wind speed at the acquisition site. When the wind speed exceeded 7 m/s the seismic acquisition was usually put on hold. However, noise specs show that the data quality also quite

***Figure 3** A shot goes off. Two parallel detonating cords of 50 m were fired simultaneously at 125 m offset at the front end of the spread.*

strongly depends on the local snow conditions, as we will briefly show in next section.

The seismic acquisition was conducted using a belted vehicle (band wagon) towing a 1500 m long snowstreamer (Figure 1) consisting of 60 geophone groups with 25 m spacing. Each geophone group was 21.5 m long and equipped with eight equi-spaced 14 Hz gimballed vertical geophones (ION Geophysical). The distance between shots was 50 m, and each shot was made by a simultaneous ignition of two 50 m long parallel lines (with approximately 1 m spacing) of detonating cord deployed in the inline direction, and with a small distance (2–3 m) from the main track of the streamer (Figure 3). The detonating cord (Nobelcord 40) was manufactured by Dyno Nobel (Orica Mining Services) and the weight of each shot was 4 kg (corresponding to 6.6 kg of TNT). The ignition point was at the front end of the line source (and the spread) with a near offset of 125 m. Figure 3 shows a blast of the detonating cords burning with a velocity of nearly 7000 m/s. Some advantages of using detonating cord are that it is flexible and easy to handle in very low temperatures, fast to deploy, and when used as a line source it gives favourable source directivity with the main amplitude lobe pointing down and backwards. Furthermore, the shots leave no permanent footprint into the ground, as required by the local jurisdiction authorities. A downside of this source configuration is that the duration of the source pulse becomes relative long, the airwave is relative strong, and as a result quite a lot of the source energy leaks into the air. The acquisition design was further set to 2 ms temporal sampling rate, 4 s recording time, a maximum common midpoint (cmp) fold of 15, with 12.5 m between each cmp point.

The recording equipment, including three Geometrics GEODE units, was mounted in the latter section of the band wagon (Figure 1) where the field operation team was also situated. Positioning of shots was monitored by a GPS receiver at the band wagon during operation, but later on coordinates were re-processed by using absolute reference points established at both ends of the profiles and at 400 m intervals.

Snow thicknesses were varying from some few decimetres to several metres. During operations the main issue with the thick snow is being able to move forward. Although glaciers are usually quite flat, some relatively strong topography may occur due to the long periodic ice dynamics. When moving upwards in loose snow, the track along the lines sometimes had to be prepared by another band wagon or caterpillar in advance before introducing the snowstreamer. When the profile lines had been positioned and secured, a total of nine people were required to perform the field operation, including supply of explosives and fuel. In the field, quality control of the seismic data was carried out using the Geode seismic controller software and Seismic Un*x, while for the subsequent inhouse processing we used Geocluster (CGGVeritas).

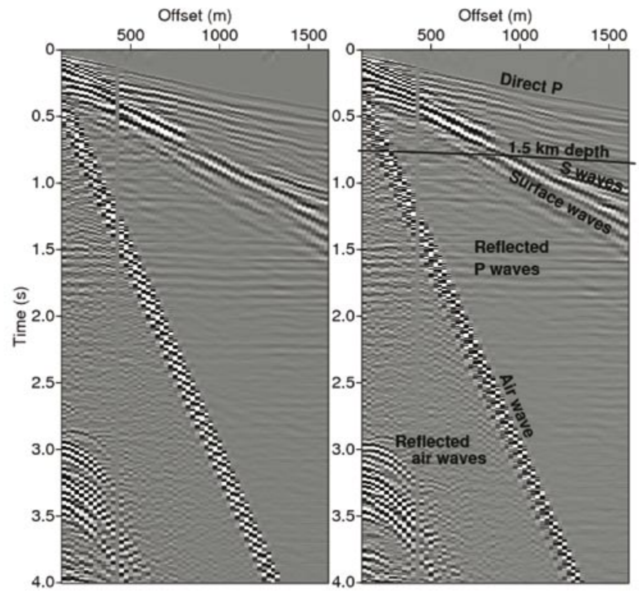

***Figure 4** Two shot gathers (50 m apart) along line 2A. Direct waves, surface waves, air wave, and echoes of the air wave from the nearby mountain sides are marked out. The expected P-wave travel time for a reflector at 1.5 km depth is also indicated.*

Data observations

Seismic events recorded on top of glaciers or permanently frozen ground usually deviate considerably from those seen in recordings made on the surface of softer unconsolidated sediments (Johansen et al., 2003). The main reason for this is the relatively high stiffness of ice which, when combined with its low density, give rise to high seismic velocities both in glaciers and frozen sediments. This may lead to situations where the uppermost layer has higher velocities than some of the layers beneath. This causes the various seismic events to occur quite differently from the usual picture seen in case of a soft surface layer (e.g., marine seismic data). For instance, the direct P-wave travelling from the source along the surface of the glacier often occurs as the first break arrival, and concurs with primary events from the shallower reflections and refractions. In general, high velocities in the overburden complicate the imaging of the shallower reflections since the primaries have a tendency to interfere with the disturbance events such as the air wave, direct waves, and surface waves. This is illustrated in Figure 4 where two shot gathers from line 2A are displayed and the disturbance events already discussed are marked out. By using the P velocity log from the nearby well as a reference, the time window in which we expect the reflection events (two-way travel time) of layer interfaces down to 1.5 km is indicated. The slopes of the direct P and S waves indicate the velocities of the glacier to be about 3.6 and 1.8 km/s, respectively. Figure 4 also shows a rather strong air wave event which only gently decreases with offset. The smooth surface of the glacier causes the air wave to attenuate slowly, which may generate strong echoes if steep mountains without vegetation are close by. Examples of such strong echoes are indicated in the two shot gathers in Figure 4. We can also see that the details of these echo events vary between the two close shot gathers. Thus, since the signatures of the echoes may change this rapidly, the design of processing schemes for removing these from the data is even more challenging than in the more general case of subsurface multiples removal. Fortunately, in our case, the air wave echoes arrive much later than the reflections of interest, and in the processing the direct air wave and later arrivals were removed by an inner mute.

The prominent surface waves indicated in Figure 4 are of Rayleigh type, since vertical geophones only were employed. Rayleigh waves are dispersive when the P- and S-wave velocities vary with depth, but the data reveal that for large ice thickness the main wave package has a velocity about the same, or a little less than the direct S wave. However, the signature of the surface waves in the shot gathers, may vary strongly across the glacier thickness. This is evident from Figure 5 where three shot gathers (140, 150, and 160) along the same line (1A) are displayed. The distance from shot 140 to 150 and from 150 to 160 is 500 m, while the thicknesses of the glacier at the midpoint of the spread at the three shot points are approximately 10, 50, and 130 m, respectively. The slope and extent of the surface wave pattern are clearly seen to vary with the thickness of the glacier, and the removal of these events also needs careful examination along the glacier profiles.

A complete image of the glacier along one line (1B) obtained from the geo-radar data is shown in Figure 6. Verti-

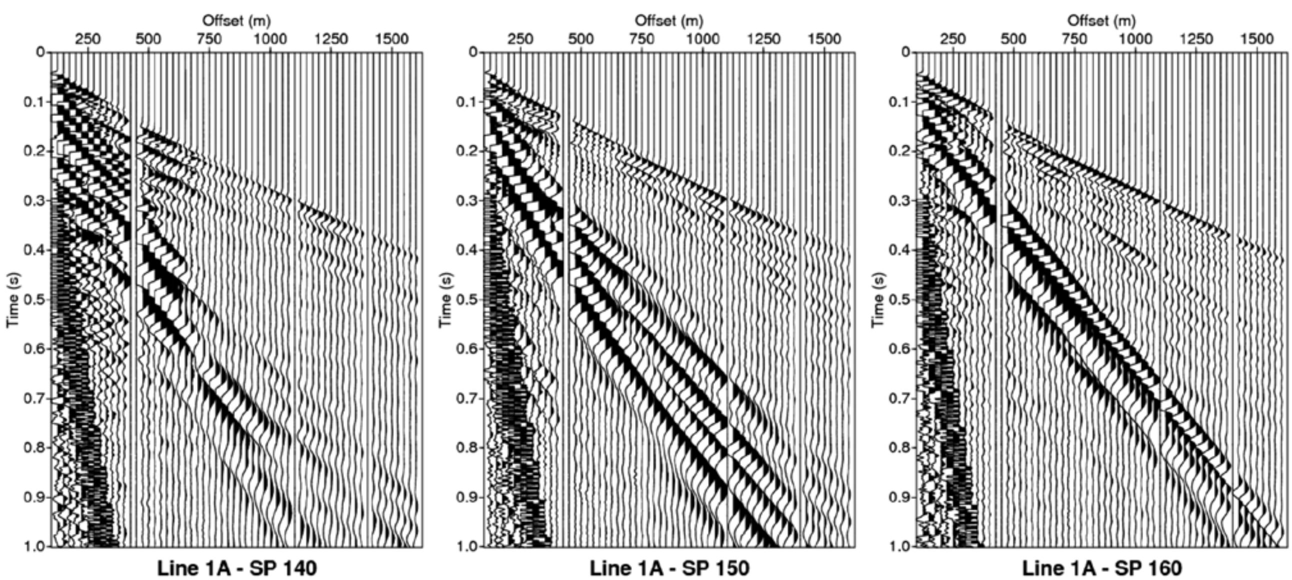

Figure 5 *Three shot gathers along line 1A where the ice thickness varies. The thickness of the glacier measured near the centre of the spread were a) 10m, b) 50m, and c) 130 m. The surface pattern is clearly seen to alter with the glacier thickness.*

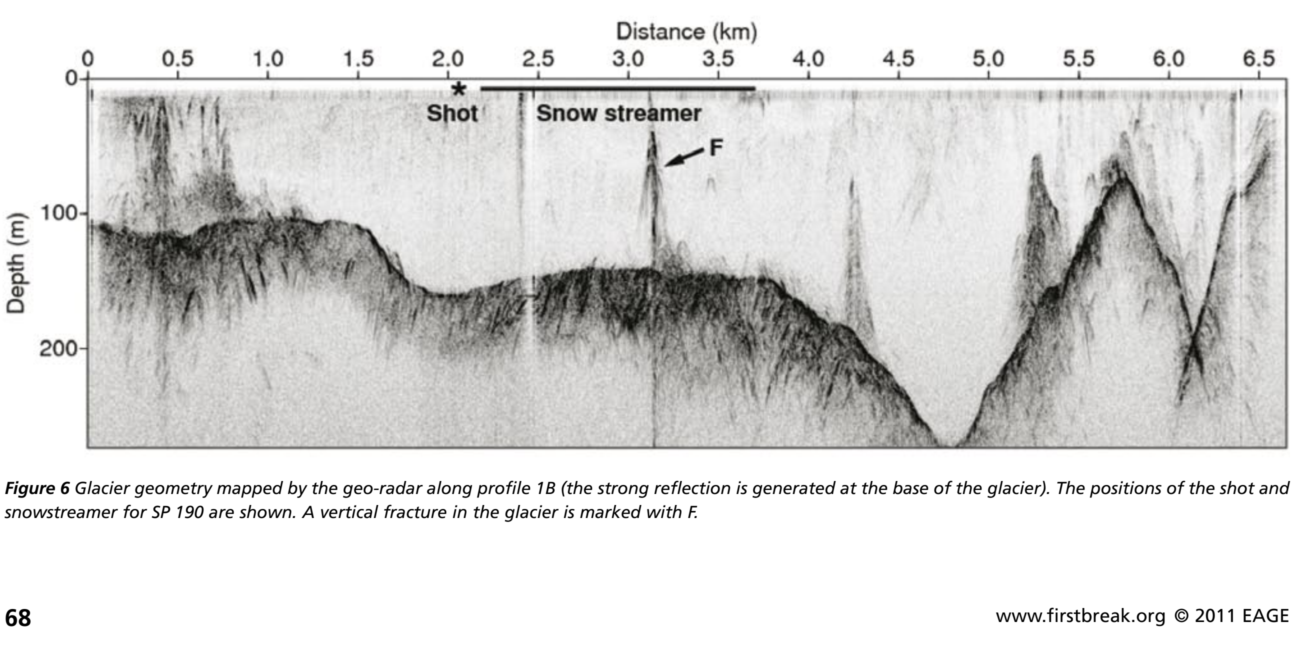

Figure 6 *Glacier geometry mapped by the geo-radar along profile 1B (the strong reflection is generated at the base of the glacier). The positions of the shot and snowstreamer for SP 190 are shown. A vertical fracture in the glacier is marked with F.*

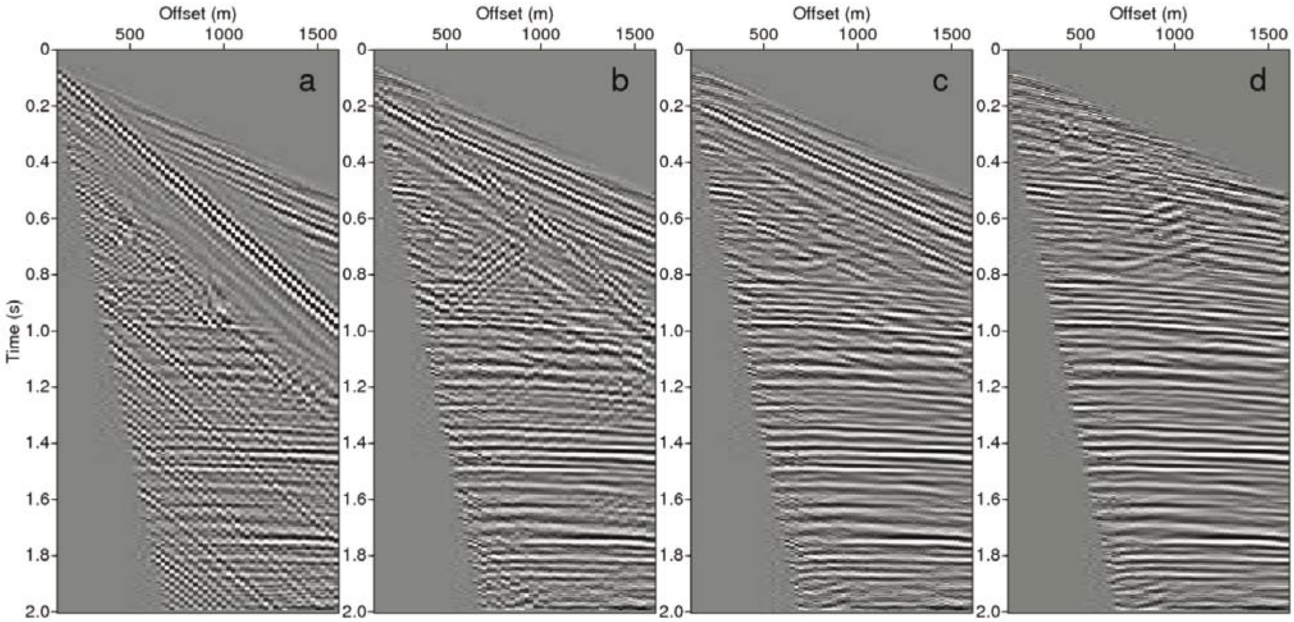

Figure 7 *Shot gather located with spread layout and shot position as defined in Figure 6. a) Raw data displayed with AGC and air wave mute; b) after removal of forward propagating surface and S-waves; c) after removal of backscattered surface and S-waves as those generated from the fracture marked in Figure 6; and d) after removal of the direct P-wave and forward scattered P-waves.*

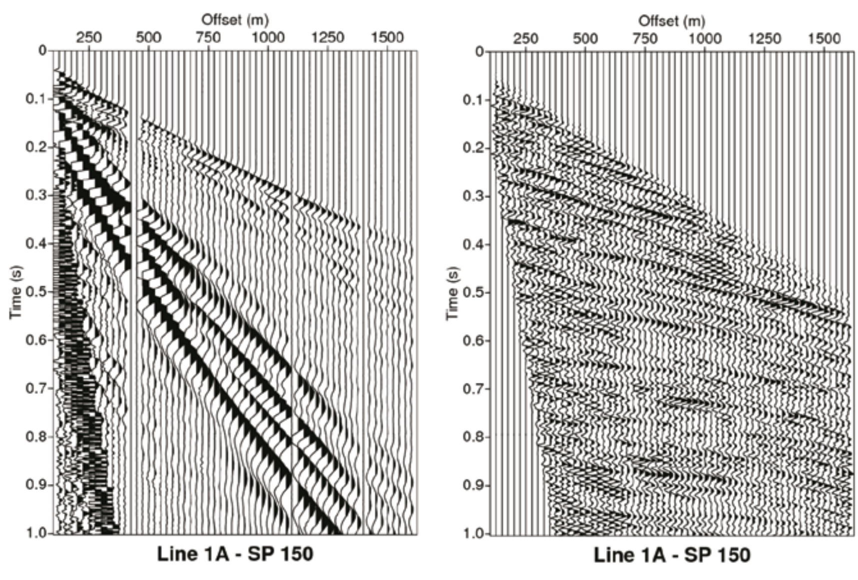

Figure 8 *Shot gather SP150 along line 1A before (a) and after (b) pre-stack processing as described in Table 1.*

cal fractures and crevasses within the glacier and its limited horizontal extension may cause unwanted side reflections and backscatters partly overprinting the main primary reflections which we want to extract. In the glacier image of Figure 6 some distinct vertical fractures are seen, and the most prominent one is labelled F. Figure 7 shows a shot gather where the streamer is located above the fracture, as defined in Figure 6. Hence, the surface position of the fracture should be approximately at 1000 m offset. A first glance of the shot gather does not particularly reveal any effect of the fracture. However, after removing some of the disturbance events mentioned (also see the figure caption), events with opposite slope to the main events, originating from this fracture, are seen in (b). In c) also, the backscattered waves are removed from the shot gather. Finally, in Figure 7d, the remaining events within the ice (apparent with a velocity less than 5 km/s, mainly horizontally travelling P-waves) have been removed. Another example of the performance of the pre-stack processing is shown in Figure 8 where shot gather SP150 along line 1A is shown before and after processing.

At wind speeds above 7 m/s the seismic acquisition was usually put on hold. However, as a test, data were acquired through a mountain pass, which almost always have winds

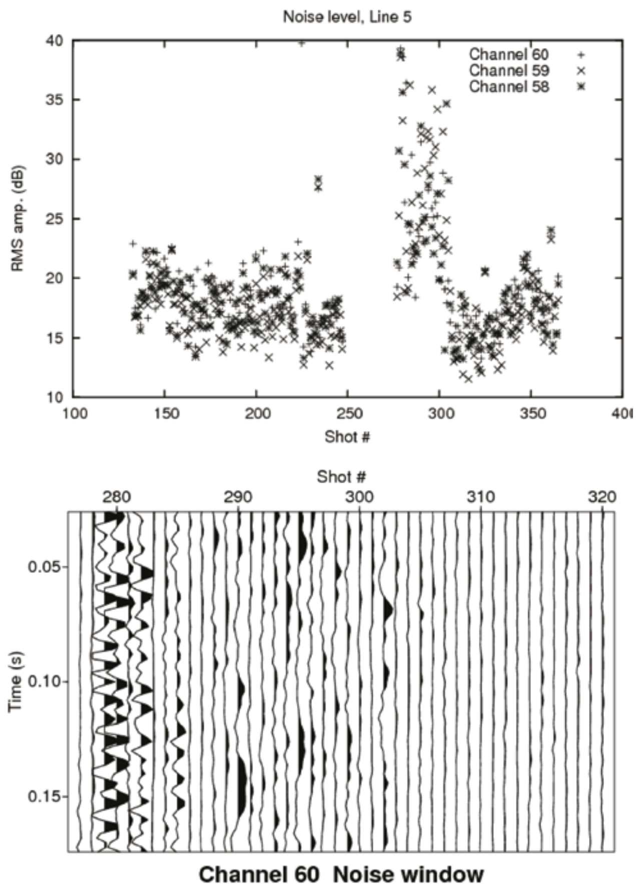

Figure 9 *Ambient noise recorded along line 5. In a) the RMS amplitudes measured in the time window before the first arrival for three far offset channels are shown. Strong wind at a mountain pass forced the crew to skip shots between SP 249 and 276. In b) traces from the far offset channel within the noise window are displayed.*

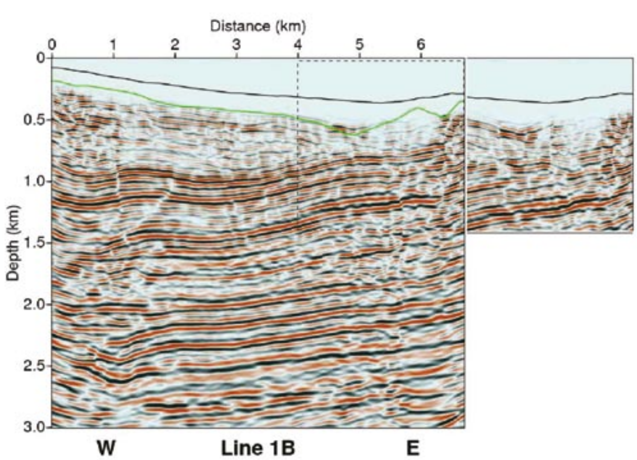

Figure 10 *Pre-stack depth-migrated seismic section of line 1B. The top and base of the glacier are indicated by the black and green lines. Clear reflections from the bottom of the glacier are seen whenever the ice thickness reaches 150 m or more. Also shown (upper right box) is part of the PSDM section obtained when not taking the glacier geometry into account.*

exceeding this limit. Snow conditions were variable, but most of the geophones were sheltered by soft snow. Figure 9 shows noise measurements made at some far offset channels in the time window before the first arrival. For the first shots after crossing the mountain pass, the wind noise was very high at far offsets, while the noise level was acceptable at short offsets (the length of the snowstreamer corresponds to 30 shot intervals). The noise level is sometimes seen to vary a lot over short distances, probably due to varying snow conditions. Consequently, if the snow is soft and the streamer follows a track sheltered by snow on each side, the seismic data acquired at higher wind speeds may potentially be acceptable.

As the data from the geo-radar provides essential input for the planning of a safe field operation at the glaciers, the above examples have demonstrated that it also gives valuable information for understanding the surface wave phenomena and noise events related to fractures. In the following example, we briefly show that the image of the glacier is also enhanced in the further processing and interpretation of the uppermost layers below the ice. Figure 10 shows a pre-stack depth migrated (PSDM) section along line 1B where the P velocity model is made by merging the profile of the glacier (i.e., geometry and a P-wave velocity of 3.6 km/s in the ice and 4.1 km/s below), well log data from the nearby well, and for the deeper events from the seismic velocity analysis. The bottom of the glacier is indicated by the green line in the seismic section. Clear seismic reflections from the bottom of the glacier are resolved whenever the thickness of the glacier reaches 150 m or more. The thinner part of the glacier is not possible to seismically detect due partly to a least offset of 125 m and partly to the interferences of the bottom ice reflection with the previously discussed disturbance events. In the main section of Figure 10 the geometry and velocity of the glacier are explicitly embedded in the velocity model, while in the upper right box no information from geo-radar has been taken into account when making the velocity model for the PSDM. We see that the reflection images obtained by the two velocity models clearly differ, again indicating that the mapping of the glacier geometry contributes to improving the seismic imaging results, and, in particular, the most shallow reflections beneath the glacier.

Summary

Seismic mapping in polar areas will get increased attention in the years to come. In this article we have given a brief review of the main impacts of the glacier conditions on the acquisition and analysis of seismic data, based on our experience from a seismic profiling campaign in the spring of 2009 at Nathorst Land, southern central Spitsbergen in the Norwegian Arctic.

The mapping of fractures and weak zones of the glacier along the planned profiles using geo-radar is, thus, of vital importance for achieving a safe field operation. However, the localization of larger vertical fractures as detected by the geo-radar, can be used to remove noise events in the seismic data generated from these. Furthermore, varying thickness of the glacier, as revealed by the geo-radar, is seen to modify the surface wave patterns. To test the seismic imaging of the shallower reflections beneath the glacier, two velocity models were input to the PDSM: one where the P-wave velocity and geometry (obtained from the geo-radar) were included, and one without this information. Clear differences in the imaging of the shallow reflection events can be seen. The above examples tell us that the geo-radar data provided information about the glacier conditions, which can help in defining and removing correlated noise events, but also in improving the seismic image of the uppermost reflections.

Acknowledgements

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