High density coverage investigation of The Austre LovénBreen (Svalbard) using Ground Penetrating Radar

Albane Saintenoy, Jean-Michel Friedt, Florian Tolle, Eric Bernard, Dominique Laffly, Christelle Marlin, Madeleine Griselin

High Density Coverage Investigation of The Austre LovénBreen (Svalbard) using Ground Penetrating Radar

A. Saintenoy*, J.-M. Friedt†, F. Tolle‡, É. Bernard‡, D. Laffly§, C. Marlin* and M. Griselin‡
*IDES, UMR 8148 CNRS, Université Paris Sud, Orsay, France
Email: albane.saintenoy@u-psud.fr
†FEMTO-ST, UMR 6174 CNRS, Université de Franche-Comté, Besançon, France
‡THÉMA, UMR 6049 CNRS, Université de Franche-Comté, Besançon, France
§GEODE, UMR 5602 CNRS, Université de Toulouse, Toulouse, France

***Abstract*—A three week field survey over April 2010 allowed for the acquisition of 120 Ground Penetrating Radar (GPR) profiles, adding to a 40 km long walk across an Arctic glacier. The profiles were acquired using a Malå equipment with 100 MHz antennas, walking slowly enough to record a 2.224 μs trace every 30 cm on the average. Some acquisitions were repeated with 50 MHz or 200 MHz antenna to improve data quality. The GPR was coupled to a GPS system to position traces. Each profile has been manually edited using standard GPR data processing, to pick the reflection arrival time from the ice-bedrock interface. Travel-times were converted to ice thickness using a velocity of 0.17 m/ns. Dual-frequency GPS mapping and snow coverage thickness were acquired during the same survey. Using interpolation methods, we derived the underlying bedrock topography and evaluated the ice volume.**

Keywords: Glacier; Ground Penetrating Radar; Ice Volume Estimation

I. Introduction

Ground-Penetrating Radar is an efficient tool for evaluating ice thickness of glaciers, internal ice structures, water channel locations and glacier thermal regime [1]–[5].

The Austre Lovénbreen is a northward-flowing valley glacier located on the Brogger peninsula, north-western Spitzbergen, Svalbarg. Its neighbouring glacier, Midtre Lovénbreen, has been extensively studied [1], [8]–[11].

Most of the time, climatic conditions do not allow the acquisition of more than few profiles across a glacier [2]. We have been fortunate enough to enjoy nice weather during the three week survey in April 2010, and we have acquired more than 40 km of GPR profiles. This paper presents first results of this high density coverage GPR survey, the estimated glacier substratum topography and the ice volume estimation of the East Lovénbreen (Svalbard).

II. Data collection

We used a Ramac GPR operating at 50, 100 and 200 MHz to collect more than 70 km of mono-offset profiles (Figure 1) over the surface of the East Lovénbreen (Svalbard) during 3 weeks in April 2010. Both the 50 MHz and 100 MHz data were collected in the form of 2806 samples and a time window of 2.224 μs. The 200 MHz data were collected in the form of 740 samples and a time window of 0.586 μs. All data were stacked 8 times on collection. Positioning of all GPR mono-offset profiles was done using a Globalsat ET-312 Coarse/Acquisition (C/A) code GPS receiver connected directly to the control unit of the GPR set to 1 measurement per second while two operators were pulling the device, walking at a peaceful rate. Each trace acquisition was triggered every 0.5 s. The average distance between each trace acquisition was calculated afterwards to 0.3 m. In addition to the mono-offset profiles, two Common Mid Points (CMP) profiles were acquired on the glacier snout using the 100 MHz antennas.

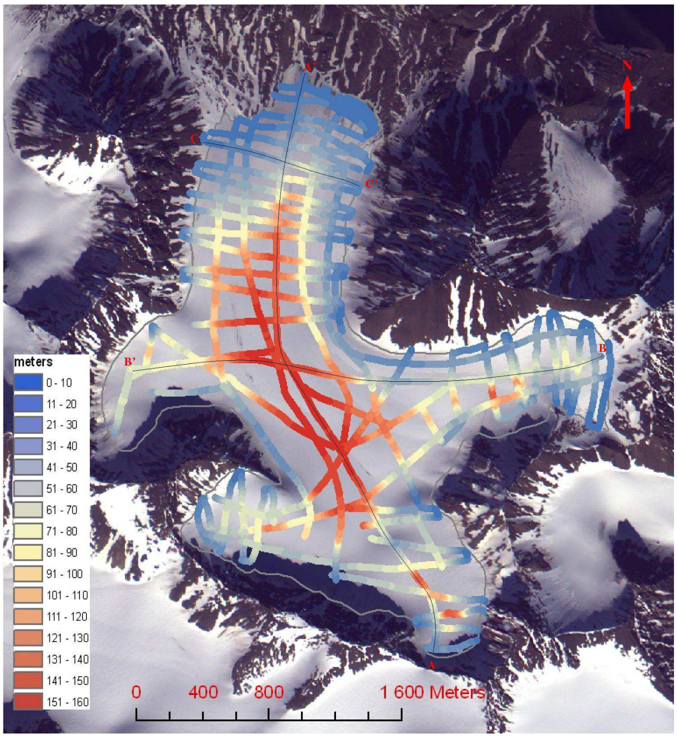

Fig. 1. GPR profiles over the East Lovénbreen (copyright FORMOSAT).

During the GPR survey, a dense elevation map was performed using GPS measurements with a snowmobile: a Trimble Geo-XH dual frequency receiver, with electromagnetic delay correction post-processing using the nearby (<10 km away) Ny-Ålesund reference dataset, provided the raw data to generate a DEM of the glacier after interpolation of the dataset.

III. Glacier structures

GPR data have been processed using Seismic Unix software [6], [7]. No migration has yet been carried out due to non-equidistant traces. A residual median filter was applied in vertical direction using a time window corresponding to the cut-off frequency of 50 MHz, each trace has been normalized to its root mean square value and band-passed filtered (25-50-150-200 MHz pass band). Each profile was vertically chopped above the arrival time of the minimum amplitude of the direct air wave (manually selected). Traces in each profile were horizontally repositioned to a constant distance step using GPS informations. Finally elevation correction was done using the altitude given by the ET312 C/A GPS. Reflection arrival times were translated using a constant velocity set to be 0.17 m/ns in the ice as in [8].

Three processed radargrams are shown on Figures 2, 3 and 4. AA' was acquired along the glacier axis toward North while BB' was acquired from East toward West across the glacier (see Figure 1). Along AA', the strong continuous reflection is interpreted as the ice/bedrock interface. At the beginning of the profile, multiple scattering occurs that could be resulting from slide rocks present in the ice. Around 700 m, the bedrock topography is rising by 50 m over a distance of 200 m creating a verrou. Many reflections are present on top of the rock bar, parallel to the bedrock surface, resulting from internal ice fractures. Going North the bedrock surface is easy to follow all the way down to the glacier front moraine. On BB' radargram, the bedrock reflection is very clear except on two areas. In the middle part of the glacier (around 1100 m away of the beginning of the profile), an area with much scattering is appearing on the deepest part of the glacier that we attribute to warm ice presence as in [8], [12]. On the last 500 m of this profile, multiple scattering is associated to slide rocks. At 1400 m along the profile, 30 m deep, some large hyperbolas are attributed to some ice embedded channels. Figure 4 shows one processed profile across the glacier tongue along the profile CC'of Figure 1. This profile crosses a supraglacial stream noticeable on summer satelite images. At the cross of this stream, the radargram shows many reflections (around 800 m along the horizontal axis). This feature can be followed on all parallel profiles acquired toward the glacier front.

IV. Ice volume estimation

In every GPR profile, the arrival time of the reflection coming from the ice/bedrock interface was picked using REFLEXW Sandmeier Scientific Software and translated into ice thickness using 0.17 m/ns velocity. A total of 129258 georeferenced data points with GPR-derived ice thickness, in addition to a glacier contour line derived from satellite pictures taken during summer (grey line in Figure 1), were interpolated over the entire glacier surface using kriging.

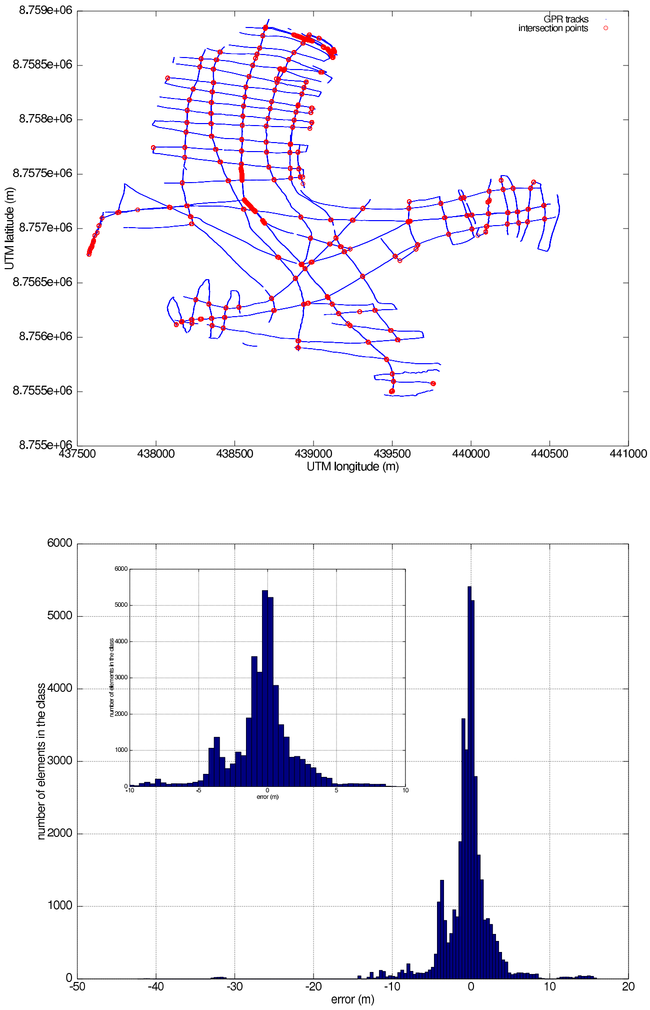

Fig. 5. Top: map of the GPR tracks (blue) and analyzed intersection points with points located less than 3 m from each other at each track intersection. Bottom: histogram of the depth difference distribution. Most points lie in a gaussian distribution with standard deviation less than 5 m, with a few outlying points yielding errors of over 30 m (probably associated with an ice-rock misinterpretation during the interface picking procedure).

Depth estimate quality assessment was performed by analyzing the error between ice-thickness estimates from independent traces intersecting: the thickness difference between points lying less than 3 m apart was computed and the histogram of the ice-thickness distribution is plotted (Fig. 5). The standard deviation of the ice-thickness distribution is less than 5 m wide, in agreement with values found in the litterature [2]. As a result, the ice volume was estimated to 0.345 ± 0.017 km^3 supposing a 5% uncertainty on ice thickness measurements.

Dual-frequency GPS measurements were used to produce a precise DEM of the glacier surface. The same uncertainty

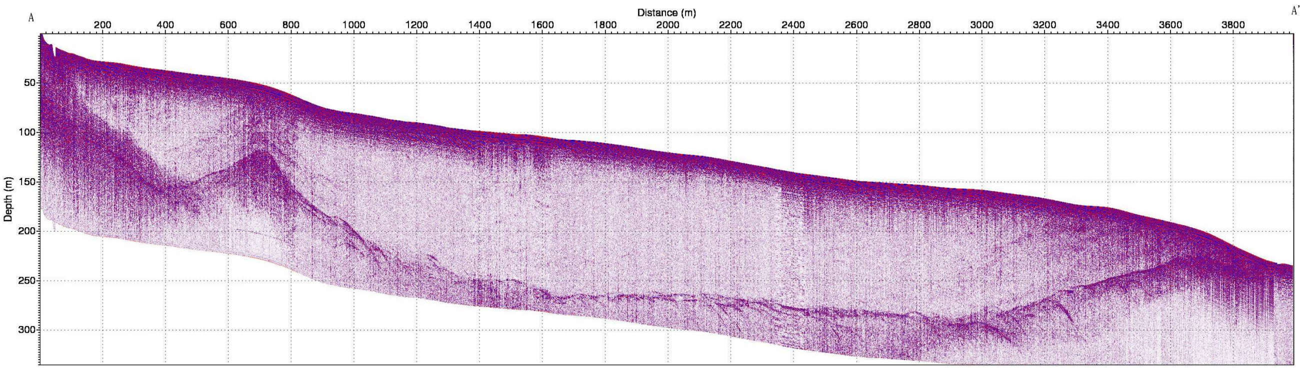

Fig. 2. Radargram AA'acquired along the glacier axis with 100 MHz antennas

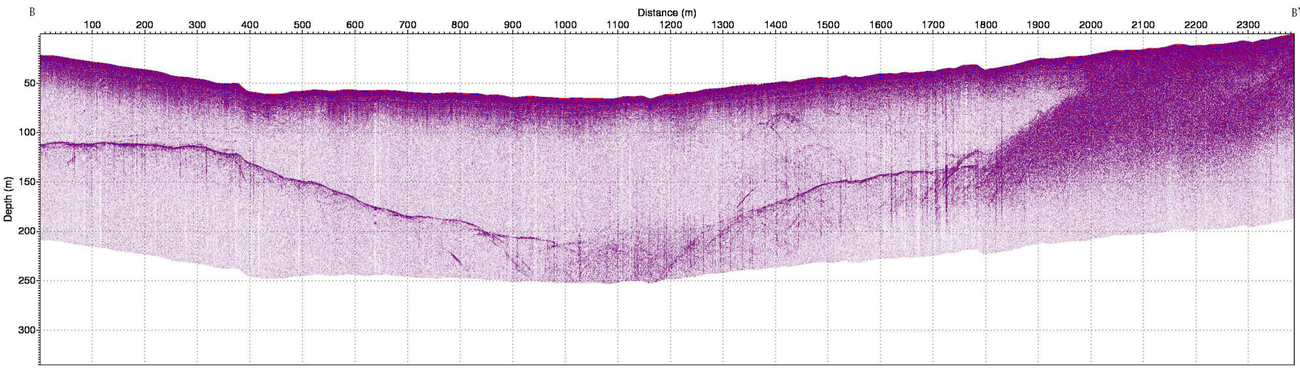

Fig. 3. Radargram BB' acquired across the glacier axis with 100 MHz antennas

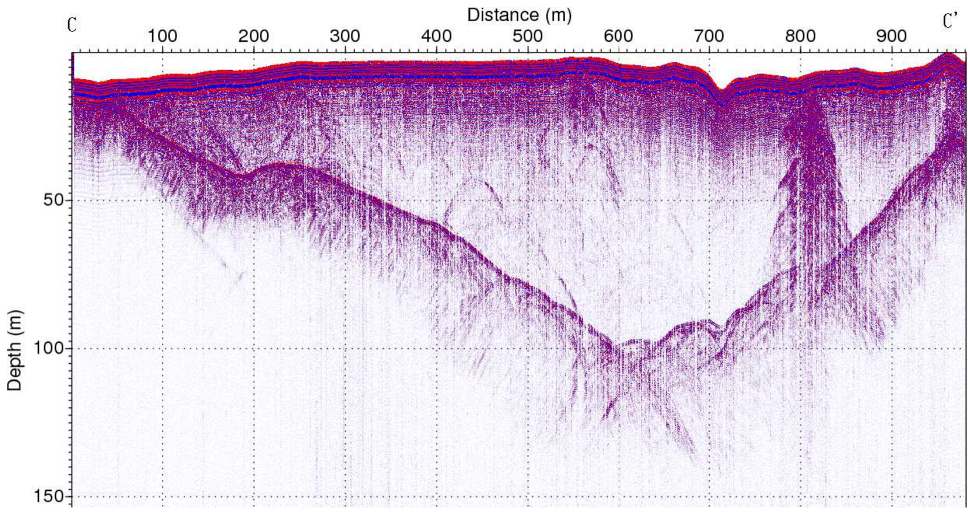

Fig. 4. Radargram CC' acquired across the glacier tongue with 100 MHz antennas

analysis carried on the dual-frequency GPR measurements yields to an altitude distribution with a standard deviation less than 0.6 m. Snow cover, evaluated through snow drilling at the time of the GPR and dual GPS measurements, was also interpolated and substracted to all other datasets. All resulting continuous datasets were derived at a 10 m spatial resolution. Ice thickness was then substracted to the glacier surface DEM to obtain a bedrock DEM (Figure 6).

Figure 7 emphasizes the asymmetry of the bedrock underneath the ice. The included radargram shows a channel in the middle. This feature is observed on every profile parallel to the one shown on Figure 7 across the glacier tongue. We think that it could be related to the transform fault presented in the geology map of [13] in between the Slatto and the Haavimb summits. The concavity of the bedrock changes of sign on each side of the channel. It could be explained by a change in the underlying rock hardness. This assymetry is seen also on Figure 6.

V. Conclusion

The high density GPR data coverage coupled to accurate DEM bring some reliable ice volume estimation necessary for future glacier mass balance. Those data bring complementary information to geology studies of the area especially in complex geological structure area. Bedrock morphology can now be used to investigate water flow path beneath the glacier. Englacial channel network could be reconstituted due to the high number of GPR profiles.

Acknowledgment

This program was funded by the ANR program blan-0310, the IPEV program 304 and the CNRS-GDR 3062 Mutations polaires. The authors would like to thank warmly AWIPEV for the logistical support in Ny-Ålesund. Tavy Murray and Adam Booth provided much helpful comments to realize this work.

References

[1] M. J. Hambrey, T. Murray, N. F. Glasser, A. Hubbard, B. Hubbard, G. Stuart, S. Hansen, and J. Kohler, "Structure and changing dynamics of a polythermal valley glacier on a centennial timescale: Midre Lovénbreen, Svalbard," *Journal of Geophysical Research (Earth Surface)*, vol. 110, pp. 1006–+, Feb. 2005.

[2] A. Fischer, "Calculation of glacier volume from sparse ice-thickness data, applied to Schaufelferner, Austria," *Journal of Glaciology*, vol. 55, pp. 453–460, 2009.

[3] T. Murray, A. Booth, and D. M. Rippin, "Water-content of glacier-ice: Limitations on estimates from velocity analysis of surface ground-penetrating radar surveys," *Journal of Environmental and Engineering Geophysics*, vol. 12, no. 1, pp. 87–99, 2007.

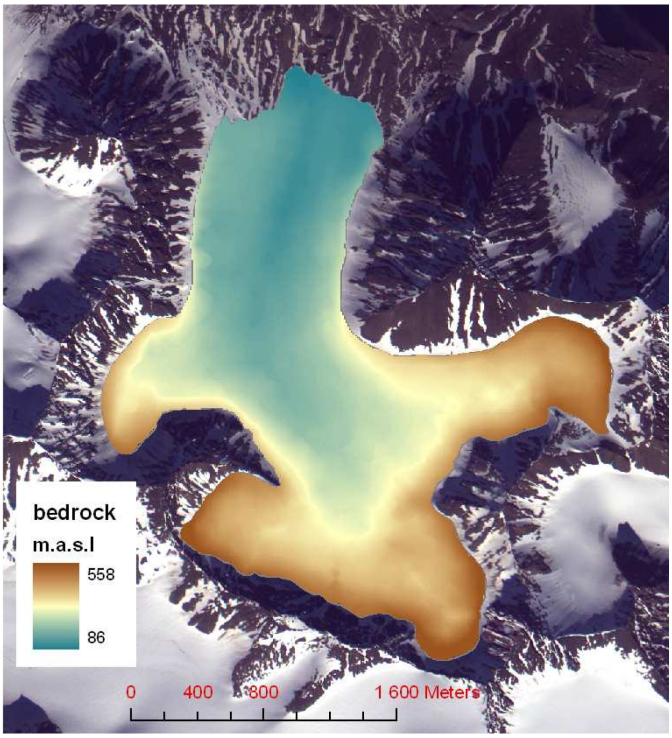

Fig. 6. DEM of the glacier substratum (copyrigth FORMOSAT).

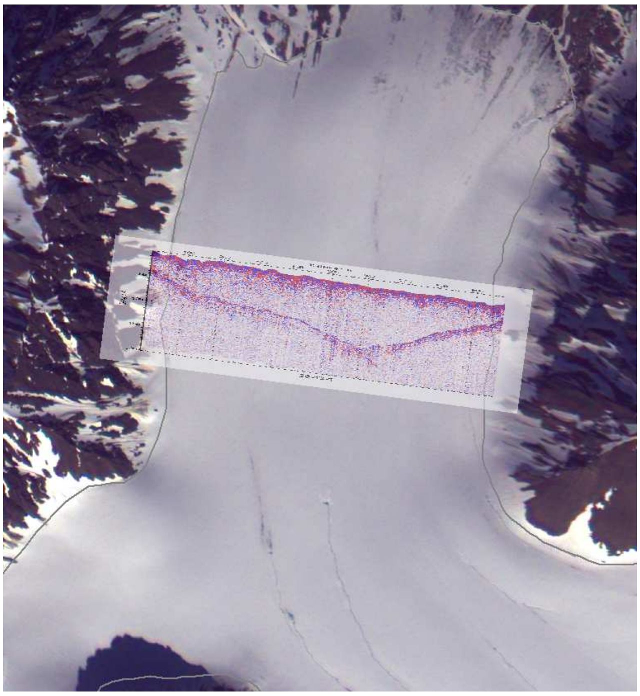

Fig. 7. Radargram across the glacier tongue positionned on a satelite image (copyrigth FORMOSAT).

[4] T. Murray and A. D. Booth, "Imaging glacial sediment inclusions in 3-d using ground-penetrating radar at kongsvegen, svalbard," *Journal of Quaternary Science*, vol. 25, no. 5, pp. 754–761, 2010.

[5] G. Stuart, T. Murray, N. Gamble, K. Hayes, and A. Hodson, "Characterization of englacial channels by ground-penetrating radar: An example from austre Brøggerbreen, Svalbard," *Journal of Geophysical Research (Solid Earth)*, vol. 108, pp. 2525–+, Nov. 2003.

[6] J.K. Cohen & J.W.Jr Stockwell, CWP/SU: Seismic Un*x Release No. 42: an open source software package for seismic research and processing, Center for Wave Phenomena, Colorado School of Mines, available at www.cwp.mines.edu/cwpcodes

[7] J.W. Jr Stockwell, "The CWP/SU: Seismic Un*x Package", Computers and Geosciences, May 1999

[8] E. C. King, A. M. Smith, T. Murray, and G. W. Stuart, "Glacier-bed characteristics of midtre Lovénbreen, Svalbard, from high-resolution seismic and radar surveying," *Journal of Glaciology*, vol. 54, pp. 145–156, 2008.

[9] D. Rippin, I. Willis, N. Arnold, A. Hodson, J. Moore, J. Kohler, and H. Bjrnsson, "Changes in geometry and subglacial drainage of midre lovnbreen, svalbard, determined from digital elevation models," *Earth Surface Processes and Landforms*, vol. 28, no. 3, pp. 273–298, 2003.

[10] D. Rippin, I. Willis, and N. Arnold, "Seasonal patterns of velocity and strain across the tongue of the polythermal glacier midre Lovénbreen, Svalbard," *Annals of Glaciology*, vol. 42, pp. 445–453, 2005.

[11] H. Björnsson, Y. Gjessing, S. Hamran, J. Ove Hagen, O. Liestøl, F. Pálsson, and B. Erlingsson, "The thermal regime of sub-polar glaciers mapped by multi-frequency radio-echo sounding," *Journal of Glaciology*, vol. 42, pp. 23–32, 1996.

[12] J. C. Moore, A. Palli, F. Ludwig, H. Blatter, J. Jania, B. Gadek, P. Glowacki, D. Mochnacki, and E. Isaksson, "High-resolution hydrothermal structure of Hansbreen, Spitsbergen, mapped by ground-penetrating radar," *Journal of Glaciology*, vol. 45, no. 151, pp. 524–532, 1999.

[13] K. Saalmann and F. Thiedig, "Thrust tectonics on Broggerhalvoya and their relationship to the Tertiary West Spitzbergen Fold-and-Thrust Belt," *Geol. Mag.*, vol. 139, pp. 47–72, 2002.