NERC-GEF report. Loan of GPR equipment

High Resolution Mapping of the Cold/Temperate Transition Surface of the Polythermal Glaciers Midre Lovénbreen and Austre Lovénbreen, Svalbard (NERC GEF Loan 811)

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Abstract

An extensive ground penetration radar (GPR) survey across the snout of the polythermal Midre Lovénbreen, Svalbard, has revealed the precise location of the downglacier transition between cold and warm ice (the cold/temperate transition surface). This work revealed that a surprisingly rapid upglacier retreat of this boundary has occurred over the past 16 years – much more rapid than the rate of snout retreat in response to a long-term negative mass balance. Such rapid response of the thermal structure to ice thinning suggests that the hydrology and dynamics of polythermal glaciers may respond in a complex way to a warming climate. Extensive GPR data were also collected over the whole of the nearby Austre Lovénbreen – the first ever such GPR survey. Although these data have not yet been analysed in detail, preliminary analysis indicates that this glacier is also polythermal, and likely behaves in a way similar to Midre Lovénbreen.

Background

It is now recognised that seasonal and intra-seasonal surface velocity variations occur on polythermal glaciers, and, as with temperate glaciers, most likely reflect short-term variations in surface water inputs to, and/or storage within, the subglacial drainage system (e.g. Rabus and Echelmeyer, 1997). The importance on dynamics of a thermal dam at the down-glacier boundary between cold and warm basal ice is acknowledged (e.g. Copland *et al*., 2003; Rippin *et al*., 2005a; 2005b), but its precise role remains poorly understood. Recent work has suggested that water backs up behind the dam in spring/early summer raising water pressures there, and then breaks through the cold-based margin in mid-late summer, with consequent impacts on basal drag and surface motion (Hodson and Ferguson, 1999; Rippin *et al*., 2005b).

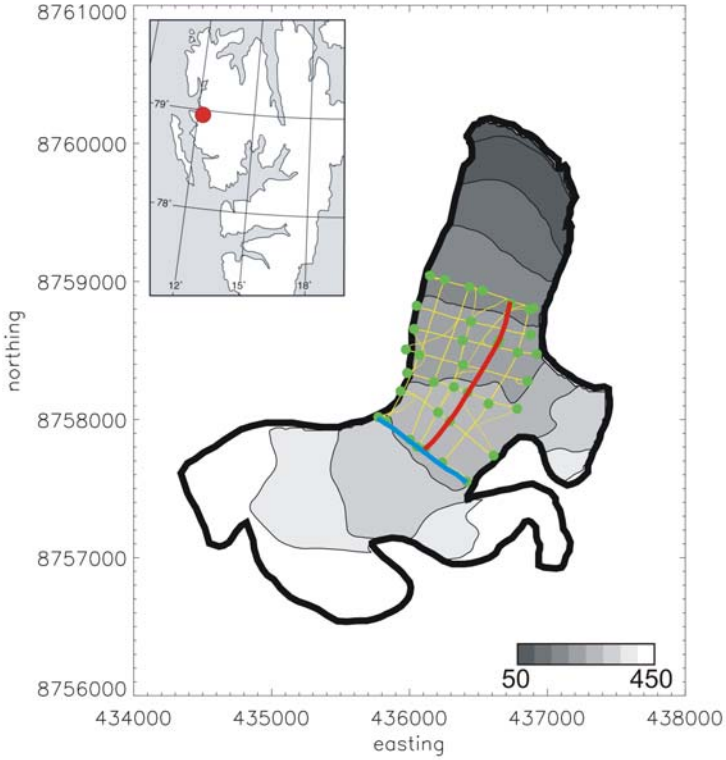

Figure 1: Surface DEM (elevations in metres) of ML derived from 2003 Lidar data (N.S. Arnold, personal communication, 2006). Yellow tracks mark radar survey lines collected in 2006 and green dots represent the start and end of each survey line. Inset shows ML marked with a red dot in Svalbard. AL is located adjacent to the east. The red line indicates the location of the down-glacier data shown in Figures 3a and b, while the blue line indicates the location of the cross-glacier data shown in Figures 3c and d.

The purpose of this project was to carry out a high density GPR surveys on both Midre Lovénbreen (ML; Figure 1)) and Austre Lovénbreen (AL). On ML, we intended to accurately define the cold/temperate transition surface (CTS), whereas on

AL, no previous GPR work had been carried out, so our intention was to: (i) collect glacier-wide data to enable the first bed DEM of it to be created; (ii) determine if the glacier is polythermal; and (iii) if AL is polythermal, accurately define the CTS. Note, that no processing has yet been carried out on the AL data, so much of the discussion here is of the ML data.

It was intended that this work would be useful for the interpretation of surface velocity and strain data that are currently being collected on ML and AL by colleagues at the Norwegian Polar Institute and the Polar Research Institute of China, with whom we are collaborating. However, the prime purpose of this work was to act as a precursor to a larger proposed programme of research which would investigate the hydraulic and mechanical mechanisms occurring before, during and after the breakthrough event, and incorporate the mechanisms into a fully coupled thermo-mechanical model of ice dynamics, and use the model to evaluate how future scenarios of climate change might influence the hydrological, thermal and dynamic characteristics of polythermal glaciers. Consequently, the key aim of this survey with respect to ML was to locate precisely where the downglacier boundary between cold and warm ice was to be found. The intention was that this boundary would be instrumented in the future in order to assist the understanding of the breakthrough events.

Determining how the thermal regime of Arctic polythermal glaciers might respond to global warming-induced climate change is of concern because the thermal regime is an important first order control on the hydrology, dynamics and thus mass balance of Arctic ice masses. It is also, therefore, important for determining the relative contribution of these glaciers to sea level rise. It is thought that global warming will be particularly marked in the Arctic (McCarthy *et al*., 2001; ACIA, 2004) further demonstrating the importance of understanding the likely resultant changes here, and the role of the polythermal structure.

Survey procedure

GPR surveying was carried out in the spring of 2006, in the form of an extensive common-offset survey of the tongue of the polythermal ML. Radar data were collected continuously using the NERC-GEF PulseEkko 100 system towed behind a skidoo. The GPR computer and console were fixed to a skidoo-trailer, and then a specially-designed antenna-sledge was towed approximately 6 m behind this trailer (Figure 2).

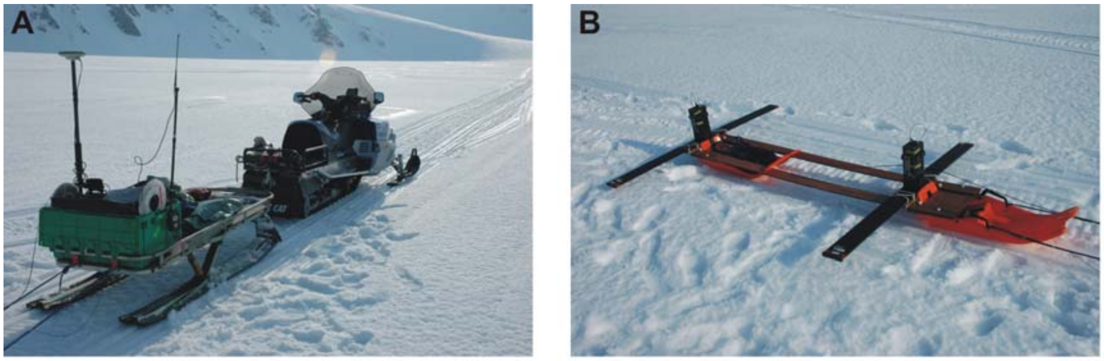

Figure 2(A): Skidoo and trailer set-up during GPR surveying. The trailer contains the GPR console and operating laptop computer. The GPS roving receiver and radio link can both be seen attached to the sledge. The GPS receiver is on the left and the radio-link antenna is on the right. (B): Custom-built GPR antenna sledge, with transmitter at the front (right) and receiver at the back (left). This sledge was located approximately 6 m behind the skidoo-trailer.

The antennas were linked to the computer and console using fibre-optic cables. Approximately 10,800 m of data were collected at a 1 m step-size over the central portion of the glacier tongue (Figure 1), at a centre frequency of 50 MHz. The antennas were positioned parallel to one another and transverse to the survey direction, thus minimising offline reflections (cf. Murray *et al*., 2007). At the same time, real-time kinematic global positioning system (GPS) data were collected every 2 seconds to accurately locate the GPR system on the glacier (using a Leica system owned by the Department of Geography, University of Hull). The roving GPS unit was located on the skidoo-trailer, and a base station was located at a fixed point.

Processing and modelling

Subsequent processing of radar data was done using the software package: ReflexW, while GPS data processing was carried out using the software package: Leica Geo Office. All GPR data were dewowed to remove low-frequency noise generated by the electronics associated with the GPR-system itself. Due to the broadband nature of the GPR signal, selective filtering of data from a single survey can be used to identify both the low frequency bed, and higher frequency scatterers, perhaps caused by liquid water (Murray *et al*., 2007). Bandpass-filtering was thus carried out with progressively increasing frequencies, until both the bed and internal scattering bodies could be identified in a single image. Finally, data were topographically corrected using a radar wave velocity of ~0.168 m ns^{-1} (and topographic data derived from the GPS data). GPR and GPS data were tied together using the time-stamp associated with each point, recorded in each set of data (the GPR computer time was synchronised with the GPS time at the beginning of every day's survey). This was done using two PulseEkko utilities: *gps2pe.exe* and *extract.exe* that together tie appropriate GPS coordinates to every GPR sample.

The glacier surface, glacier bed, and the boundary between areas of warm and cold ice were picked using the package ReflexW. We interpret regions of ice that are relatively 'clean' (i.e. contain no/minimal scatterers) as cold ice that contains no liquid water, while regions that are relatively 'dirty' (i.e. contain a large concentration of scatterers) as warm ice that contains significant amounts of liquid water. These data were used to map the thickness and extent of temperate and cold ice in the glacier tongue, and were compared with previous GPR surveys collected in May 1990 (Björnsson *et al*., 1996), and May 1998 (Moore, unpublished data; cf. Rippin *et al*., 2003).

Data quality (including examples)

Data during this survey were collected continuously, in order to maximise spatial coverage in a relatively short amount of time (time limitations became even more pressing by adverse weather conditions on a number of occasions, reducing the time available to collect data). As a consequence, the antenna were not coupled directly with the snow surface during data collection (they hovered a short distance above the surface to avoid damage while moving across the glacier), and the data were not stacked. Consequently, the resultant GPR data are not as *clean* as they might otherwise have been, had each point been collected while stationary. The trade-off between data-quality and data-volume was carefully considered during the survey-planning stage, and the reduction in quality was considered acceptable, given the desire to collect large amounts of data. Despite this trade-off, the results were considered to be of sufficiently high quality for their designated purpose (Figure 3).

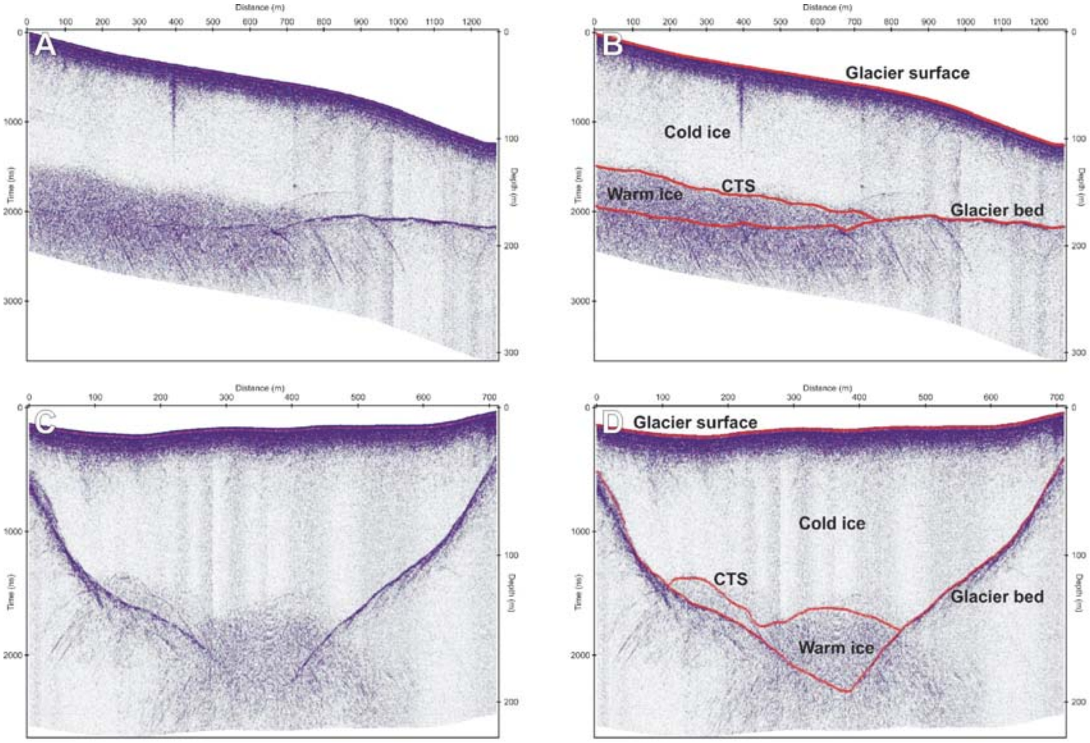

Figure 3(A): 50 MHz GPR transect parallel with the glacier centreline (flow direction from left to right; red line in Figure 1). The glacier surface is clearly visible as is the bed to the right of the image. To the left, the bed becomes obscured by a zone of intense scattering, which we interpret to be warm ice. (B): identical image to (A), but with red lines marking the glacier surface, bed and cold/temperate transition surface (CTS), as well as zones of cold and warm ice. (C): 50 MHz cross-glacier GPR transect (blue line in Figure 1). The glacier surface is clearly visible as is the bed across most of the image, apart from in the central, deepest portion. Here, the bed is obscured by a zone of intense scattering, which we interpret to be warm ice. (D): identical image to (C), but with labelling as in (B).

Interpretation to date

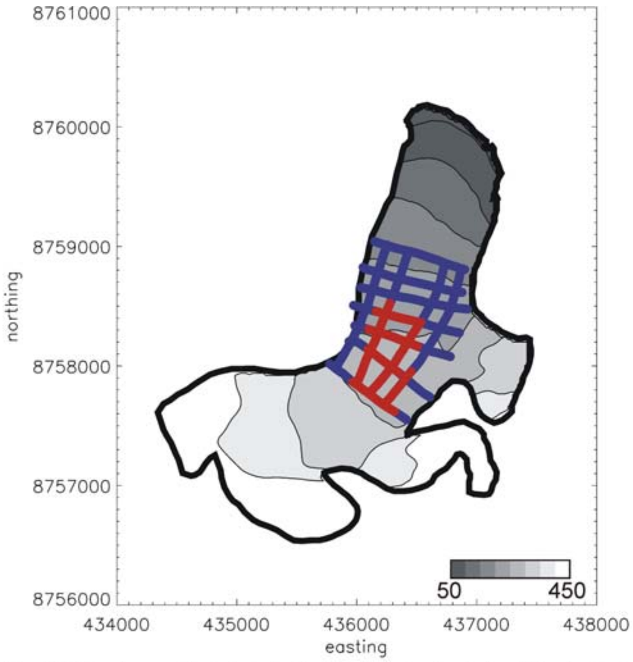

Figure 4: GPR tracks across ML, shaded so that blue indicates tracks where ice is cold throughout, and red indicates areas where there is some thickness of warm basal ice. The downglacier boundary between areas where there is warm basal ice, and where ice is cold throughout (the CTS) is clearly visible. Tracks overlie a surface DEM (cf. Figure 1).

We interpret areas of minimal/no scattering to be cold, water-free ice, and regions of intense scattering to be warm ice containing water. Figure 4 shows the location of all survey-lines across ML (cf. Figure 1), shaded blue to reflect the presence of ice which contains no internal scattering (cold ice), or red where there is a layer of basal scattering present (warm ice). The figure shows that over much of the surveyed area, there is minimal internal scattering, and thus cold ice dominates. However, in a central portion of the surveyed area, there is a layer of ice above the bed in which internal scattering is present (cf. Figure 3). This basal scattering zone likely extends upglacier beyond the limits of our survey, but the extent of our data-coverage do not allow us to comment on this.

Preliminary findings

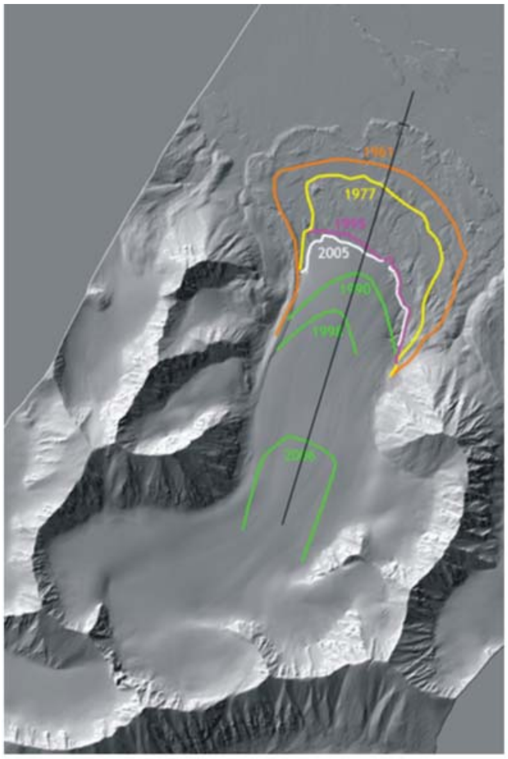

Figure 5: Location of CTS in 1990, 1998 and 2006 (green), in relation to the terminus position of ML in 1961 (orange), 1977 (yellow), 1995 (pink) and 2005 (white).

These data enable us to map the lateral extent of warm-based and cold-based ice, which may be compared with similar maps based on previous GPR surveys collected in May 1990 (Björnsson *et al*., 1996) and May 1998 (Moore, unpublished data; cf. Rippin *et al*., 2003). Figure 5 shows that the boundary between warm- and cold-based ice has shrunk laterally, but more particularly, has shifted upglacier over the 16 years. In 1990, the downglacier limit of the CTS was ~200 m from the glacier terminus (as identified from the 2003 DEM (N.S. Arnold, personal communication, 2006)). In 1998, the CTS was ~500 m from the snout, while in 2006 the CTS was ~1450 m from the snout (Figure 5). In 2006, the thermal dam was thus ~1250 m further upglacier than it was in 1990. To put this into context, the glacier average mass balance between 1990 and 2005 was -6.5 m w.e. (-11.5m w.e. since 1977), and the amount of snout retreat between 1995 and 2005 was 50 m (550 m since 1977). So, the boundary between warm and cold ice has shifted upglacier at a rate far greater than that at which the snout has retreated.

Conclusions

Midre Lovénbreen appears to have experienced significant shrinkage of its temperate core, probably as a consequence of sustained negative mass balance over recent years. Nevertheless, the rate at which this retreat has occurred is surprising, and suggests that there is a very rapid response of a glacier's thermal structure to changing mass balance. Under a projected warming climate, a continuing negative mass balance of such polythermal glaciers is likely. However, the role of an enlarging, impermeable, cold snout may be significant for drainage of subglacial water. Furthermore, increasingly restricted drainage through the snout has implications for glacier dynamics, and also for the further mass balance response to a changing climate. Incorporating such potentially complex mass balance feedbacks into ice sheet models would seem to be of the utmost importance.

As outlined above, this work was carried out with the express intention of using the results to submit a NERC Standard Grant application to study: 'Hydrological / dynamic coupling on polythermal glaciers'. Grant application NE/E005934/1 was submitted to NERC on 30th June 2006, but was sadly rejected. Resubmission in a revised form is being considered.

Finally, No details concerning the results from AL are presented here. As yet, these data have not been analysed, although some very basic preliminary processing has been carried out – sufficient to assess the data-quality and confirm that the glacier also appears to be polythermal.

Publications (including proposed, in preparation, submitted, in press and published)

Papers and abstracts

Rippin, D.M., I.C. Willis and J. Kohler. (in preparation). Changes in the thermal regime of the polythermal Midre Lovénbreen, Svalbard.

Rippin, D.M., I.C. Willis and J. Kohler. (in preparation). The geometry and thermal regime of Austre Lovénbreen, Svalbard.

Rippin, D.M., I.C. Willis and J. Kohler. 2007. Changes in the thermal regime of the polythermal Midre Lovénbreen, Svalbard. *Geophysical Research Abstract*, EGU2007-A-03737.

Willis, I.C., D.M. Rippin and J. Kohler. 2007. Changes in the thermal regime of the polythermal Midre Lovénbreen, Svalbard. *The Dynamics and Mass Budget of Arctic Glaciers: Extended abstracts*. Institute for Marine and Atmospheric Research Utrecht, Utrecht University, The Netherlands, 130-133.

Conference presentations

Rippin, D.M., I.C. Willis and J. Kohler. 15th-20th April 2007. Changes in the thermal regime of the polythermal Midre Lovénbreen, Svalbard. European Geosciences Union General Assembly. 15th-20th April 2007, Vienna, Austria.

Willis, I.C., D.M. Rippin and J. Kohler. 15th-18th January 2007. Changes in the thermal regime of the polythermal Midre Lovénbreen, Svalbard. Workshop on the dynamics and mass budget of Arctic glaciers. Pontresina, Switzerland.

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Rippin, D.M., D.G. Vaughan and H.F.J. Corr. (in preparation). The role of basal roughness on the flow dynamics of Pine Island Glacier. *J. Geophys. Res*.