

Geophysical techniques to measure the hydrothermal structure of Storglaciären, spring and summer 2009

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Introduction

Kebnekaise (2104 m a.s.l.) is the highest mountain in Sweden and is located in Lapland, about 150 kilometers north of the Arctic Circle; there are no higher peaks further north in Europe (Figure 1). It occupies the northern area of the Scandinavian Mountains, a mountain range that runs through the Scandinavian Peninsula. The northerly location, combined with the high altitude and the moisture from the North Atlantic Ocean has caused the formation of many icefields and glaciers which are classified by glaciologists as small glaciers. These fast retreating ice masses are contributing the majority of current observed, glacier-derived sea-level rise (Meier *et al.*, 2007). It is therefore particularly important to monitor their temporal evolution and to understand the dynamics which regulates their thermal behaviour and flow. In this report we illustrate the experiments conducted for two field seasons (Spring and Summer 2009) on Kebnekaise's best known glacier: Storglaciären.

Scientific background

Recent large retreats and sudden variations in the dynamics of glaciers all over the globe have directed the attention of glaciologists and climate scientists to the difficult task of predicting the future behaviour

of ice masses. What will happen to the Greenland ice sheet, which contains 7 m of sea-water equivalent, in the next few centuries? How will the landscape and the socio-economic situation change in countries (for example, in the European Alps) where glaciers represent a significant economic resource (for water supply, mountain tourism, summer skiing)? To answer these questions we need to improve our predictive models of glaciers and ice sheets, and to achieve this we need to understand better the properties of the material that we are considering: glacier-ice.

Many models assume ice-properties are uniform within a glacier. This is not true, especially in the case of polythermal glaciers (widespread throughout the Arctic and high Alpine regions). Such glaciers consist of both cold (below pressure melting point) and warm (at pressure melting point) ice, and both ice temperature and water content are known to vary substantially within them. Ice deformation is sensitively dependent on both temperature and water content: for example, laboratory studies have indicated that a 1% increase in water content can increase a sample's deformation rate by ~400% (Duval, 1977). This sensitivity means that the flow rate of both temperate and polythermal glaciers is strongly affected by the distribution and concentration of water within the ice. It is therefore critical that methods for measuring water content of temperate and polythermal glaciers are developed and validated.

This expedition is part of the authors' recent research (Murray *et al.*, 2000; Pettersson *et al.*, 2003, 2004; Pettersson, 2005; Murray *et al.*, 2007; Gusmeroli *et al.*, 2008; Barrett *et al.*, 2008; Endres *et al.*, 2009; Gusmeroli *et al.*, 2010a, 2010b) which has explored several different geophysical techniques to measure and map spatially the distribution of englacial water within glaciers. In fact the propagation speed of radar and seismic waves is known to be decreased by increased glacier-ice water content. Improvement in the knowledge that we have on this topic will represent a valuable step forward in many important processes in



Figure 1. Location map of the Kebnekaise massif.

glaciology such as:

- a) Rheology of ice: The flow parameter, used to quantify how ice deforms and flows, is strongly related to the amount of the liquid water within glacier ice. Cold ice without water is known to be stiff, while warm ice with water inclusions is soft. This has, however, never been directly validated in the field.
- b) Polythermal dynamics of glaciers: The liquid-water content is known to be one of the most important factors in the thermal stratification of glaciers. Quantifying it is the first step for a more comprehensive understanding of how polythermal ice masses will change in response to current climate warming.
- c) Englacial hydrology: Several highly debated processes such as flow instabilities, dramatic accelerations and decoupling of a glacier from its bed are thought to be related to the storage and the movement of liquid water within glaciers. New light on these processes is required since under the current warm climate conditions interactions between the climatic inputs (e.g. melt water produced during a hot summer) and the glacier system are strongly enhanced.

Part I – Spring 2009

Summary

An extensive ground-penetrating radar dataset has been acquired at the glacier Storglaciären, Northern Sweden, during 35 days in spring 2009 (March–April). The number of person/days in the field was 48. The field team was based at the Tarfala Research Station, one hour skiing from the glacier. This dataset complements a previous borehole geophysics dataset acquired during 4 week field set in summer 2008. The field season was enormously facilitated by the weather, which allowed an almost continuous daily data collection on the glacier. In this expedition we tested several different ground-penetrating radar surveys to map and measure the spatial distribution of englacial water within the glacier. Multi-frequency and multi-polarisation common offsets (CO) surveys were acquired to estimate the dimension and spatial orientations of englacial water bodies, while wide angle reflection refraction and common mid-point surveys were collected to quantify subsurface variations in radar wave velocity and radar attenuation which are due to water-content. Several common offset lines were also acquired in the accumulation area and at the terminus of the glacier meaning that a comparison between different hydrological regimes within the glacier is possible. Finally the polythermal structure of the glacier has been mapped at high spatial resolution; this will allow a comparison between previous measurements and will bring new insights about the response of polythermal glaciers

to recent climatic warming. In this report we discuss scientific background, logistics, field methodology and preliminary results of the expedition.

Research aims

We originally planned to conduct radar and seismic surveys in several areas on the glacier. We chose to delay the seismic acquisition to subsequent field seasons and we focused on radar-only, this was because we had the opportunity to use both the Swansea and Stockholm Universities radar system with 4 different antennas (25, 50, 100 and 200 MHz). We also judged it more realistic and logically less challenging (not least for shipping costs) to focus in obtaining a robust dataset using one technique only.

The main field area targeted was that previously investigated by borehole geophysical techniques during the summer 2008. During that field season we collected borehole radar and seismic surveys in order to obtain high resolution vertical profiles of the propagation velocity of both geophysical signals, which is known to decrease as the water content increases, varies with depth (Gusmeroli et al., 2010a; 2010b).

The main objectives of the spring 2009 field season were to:

- Undertake multi-frequency ground-penetrating radar surveys in the area investigated in the summer. By repeating the same radar profile using antenna of different frequencies is possible to estimate the dimensions of the objects causing reflection within the glacier which, in the case of temperate ice, are water bodies (Pettersson, 2005; Barrett et al., 2008).
- Undertake multi-polarisation ground-penetrating radar surveys in the area investigated in the summer. By repeating the same radar profile changing the orientation of the antenna is possible to determine whether water bodies causing reflection within the glacier are orientated in a particular direction or not (Barrett et al., 2008).
- Obtain multi-azimuthal common mid-point (CMP) radar surveys in the area investigated in the summer. In this survey the receiver and the transmitter are progressively moved apart from a fixed mid point. The CMP technique is known as the standard method for obtaining estimates of how radar velocity changes with depth in the glacier, and in our multi-azimuthal experiment we aim to understand how radar velocity changes by changing the direction of survey (e.g. going cross or up glacier).
- Obtain multi-azimuthal wide angle reflection and refraction (WARR) radar surveys in the area investigated in the summer. These surveys are similar to CMPs since the main aim of WARR is to measure the propagation speed of radar waves. In this survey the transmitter is fixed and the receiver is progressively moved away from it.
- Measure ice thickness and general thermal state of the area investigated in the summer.

- Continue P. Jansson and R. Pettersson project of mapping, extensively and with considerable detail, the polythermal structure of the glacier. The way how polythermal glaciers are changing their thermal structure is in fact an important proxy to understand their response to climate changes. Storglaciären thermal structure has been mapped in 1989 and 2001, and a comparison between the two maps show that the cold surface layer experienced complex thinning of about ~ 8.3 meters on average in 11 years (Pettersson et al., 2003). A new map will enable a further comparison and will provide new insights of polythermal glacier's response to climate changes.
- Conduct ground-penetrating radar surveys to obtain information about relatively unknown areas of Storglaciären (e.g. the terminus and the accumulation area). These surveys can also be used to locate future drilling spot by identifying potential study areas.

Field logistic

After the initial transportation of the equipment on to the glacier using a snow-scooter on the 25.03.2009, the rest of the field season was entirely done by using ski as way of moving from the station to the glacier, around the glacier, and back from the glacier to the station. All the field team was chosen to have some experience in ski-mountaineering, travelling and working in the winter mountain environment. The ski equipment used by the field team is similar to the one used in the classic Alpine ski-mountaineering international competition

such as Mezzalama Trophy and Patrouille des Glaciers.

Transmitting avalanche-beacon, shovel and snow probe were included in everyone's kit when working on the glacier. The field team did not work as a roped team since Storglaciären is a very safe glacier (especially in the spring season where the glacier is thickly covered by snow), however all the team wore a safety harness and dangerous, potentially crevassed areas were always avoided.

We used two commercially available Måla Geoscience RAMAC ground-penetrating radar systems; one was borrowed from the University of Leeds while the second is owned by Stockholm University and located at Tarfala Research Station. Both systems comprise of a transmitter, a receiver, a control unit and optic cables. A set of different antennas was also used to undertake multifrequency (25, 50, 100 and 200 MHz) surveys. Those items were left overnight on the glacier into boxes and ski bags secured to a stake permanently planted in the ice while transmitter, receiver, control unit batteries and the field-laptop were carried back to the station at the end of the field-day to re-charge.

Study area

We concentrated the radar measurements in three different parts of the glacier (see Figure 2):

- (A): The upper ablation area of the glacier located approximately at 1350 m of elevation. This area was extensively investigated by borehole geophysical surveys in the summer. In (A) the glacier is polythermal and a ~ 20-25 meters thick cold

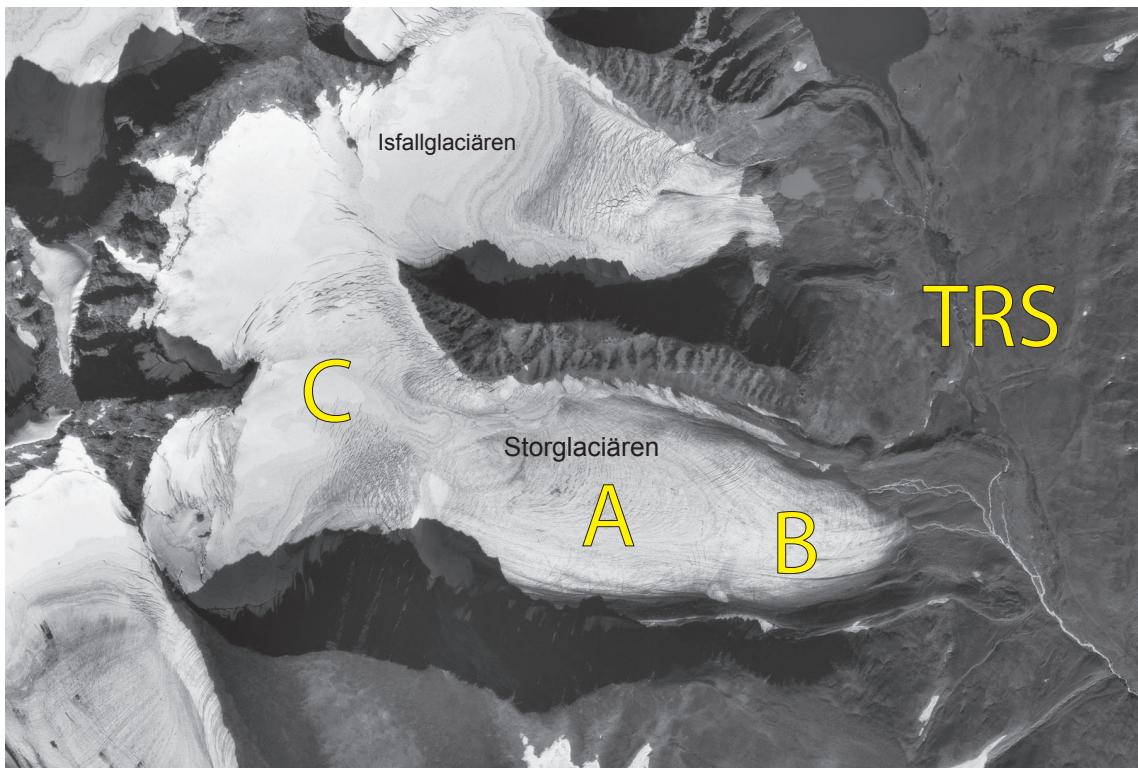


Figure 2. Summer aerial photo of the Tarfala valley with indications of the areas investigated in spring 2009. A: upper ablation area, B: terminus, C: accumulation area. TRS: Tarfala Research Station.

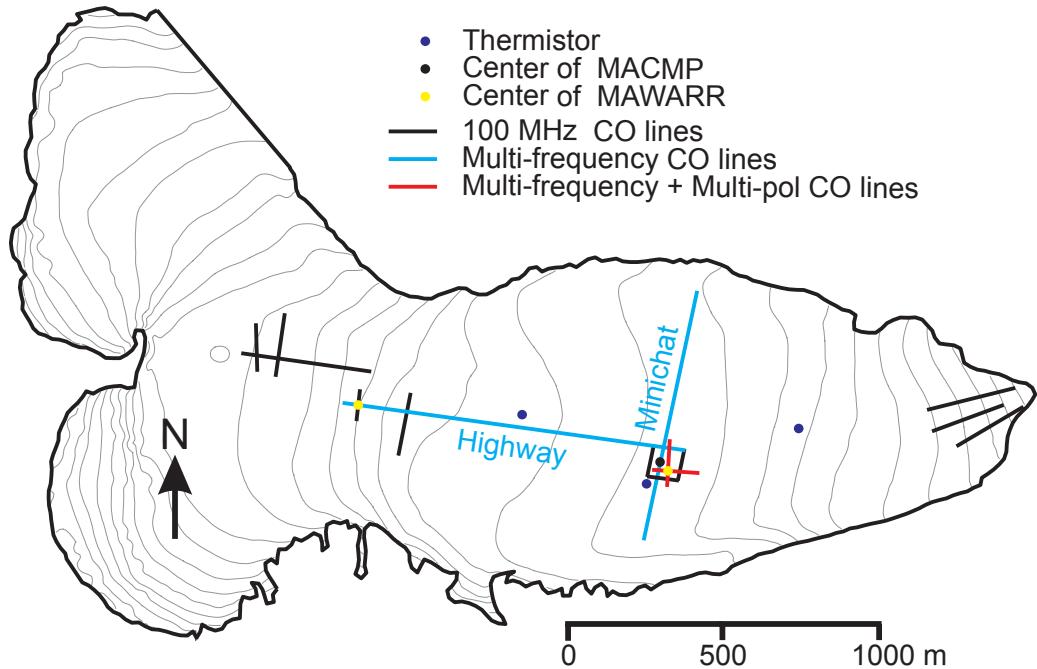


Figure 3. Map of the experimental surveys collected in spring 2009.

surface layer overlie a temperate core.

- (B): The terminus of the glacier. In this area the thermal state of the glacier changes from being polythermal (and therefore warm-based) to entirely cold (frozen to its bed).
- (C): The accumulation area where firn and newly formed ice is annually produced. In this area the glacier is thought to be fully temperate since the presence of the snow-cover insulates and protects the ice from the cold wave. Furthermore the percolation and refreezing of melt-water within the porous firn generates an important amount of heat which contributes in maintaining the ice temperate.

Data summary

The dataset acquired can be divided into an experimental part and a monitoring part. The experimental part comprises experiments which will be used to obtain new information about Storglaciären englacial water system and glacier dynamics (see Figure 3 for a map of the experiments); whereas a detailed network of GPR surveys constitutes the monitoring-mapping part (Figure 4).

We undertook a variety of geophysical surveys:

- Common offset (CO) surveys: These surveys are typically used to map ice thickness and thermal structure. We acquired several CO profiles by hauling a plastic sledge with transmitting and receiving antennas mounted 2 m apart. A stop-and-go survey method was applied by holding motionless the system at 0.5 m sampling intervals. Multi-frequency profiles were acquired by repeating the same survey line using 4 different frequencies (25, 50, 100, 200 MHz). Multi-polarisation surveys were also
- acquire by repeating the same survey line using 16 different polarisations (orientations of the 100 MHz antenna). This means that the survey lines indicated with red color in Figure 3 have been repeated 19 times (1x25 MHz, 1x50MHz, 1x200MHz and 16x100MHz). Two long lines named Highway and Minicha have been repeated with all the four frequencies. Several reconnaissance 100 MHz CO surveys (black lines in figure 3) were also acquired to explore different areas of the glacier and to compare the radar-derived thickness of the cold surface layer to that inferred by direct measurement of temperatures using thermistors (blue point in figure 3).
- Common mid-point (CMP) surveys: CMPs are commonly used to measure propagation speed of radar waves in depth. We obtained a full multi-azimuthal CMP in the upper ablation area of the glacier, centred in the point indicated by the black dot in Figure 3. CMP surveys are collected by progressively offsetting the transmitter and receiver symmetrically about a central point. 4 100 m long CMPs centred in the same point were acquired covering 4 different azimuths: N-S, NE-SW, E-W, NW-SE.
- Wide angle refraction, reflection (WARR) surveys: Similar to CMPs but probably more accurate in quantifying the dissipation of the radar energy, WARR are obtained by leaving a transmitting antenna fixed and progressively offsetting the receiver. We obtained 4 WARR in two different areas of the glacier (yellow points in 2.5). These surveys can also be treated as multi azimuthal WARR since for every fixed point 4 surveys 50 m long were acquired.

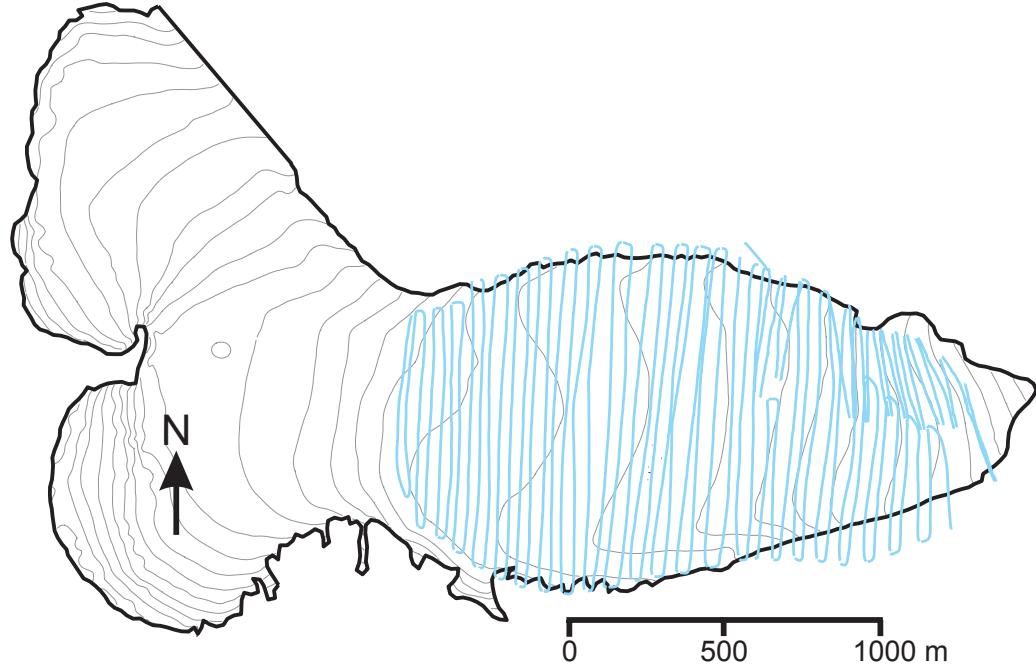


Figure 4. The mapping of the polythermal structure of the glacier was done with several 100 MHz profiles. The dataset shown in this figure was mainly collected by P. Jansson and is part of Jansson and R. Pettersson's recent research (Pettersson et al., 2003) on polythermal glaciers.

A detailed mapping of the polythermal structure of the glacier have also been performed to continue P. Jansson and R. Pettersson project using 100 MHz CO surveys (see Figure 4).

Preliminary results

Figure 5 show the 25 MHz CO profile Minicha. The thermal structure of the glacier is well represented in

our data since scattering does not occur in the upper area, known to be cold-water-free ice. Diffuse scattering thought to be due to englacial water bodies is observable in the lower part of the glacier, known to be temperate ice. The presence of these water bodies seems to attenuate radar energy and reflections from the bed, necessary to measure ice thickness, are only visible when low-pass filtering is applied.

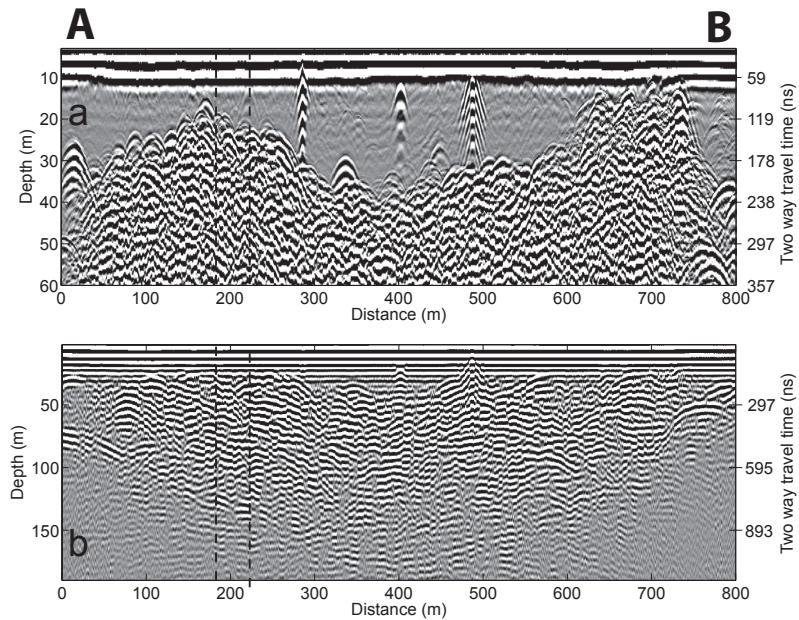


Figure 5. 25 MHz CO line Minicha, A and B represents the southern and the northern ends of the line respectively. The area in between the two dashed lines is the area investigated in the summer. a) unprocessed radargram used to measure the thickness of the cold surface layer. b) low-pass filtered radargram which shows a weak reflection starting at around 70 meters depth; these reflections are interpreted to be the glacier-bed. The depth scale is computed by using a constant velocity model of 0.168 m/ns.

A sample of the 100 MHz CO lines collected at the terminus is also shown (Figure 6). This area seems to be particularly interesting since the glacier changes its thermal state from polythermal to fully cold. Preliminary results clearly show the reflections from the bed and several internal reflectors which clearly dip up-glacier (especially in the northern profile). The transition between warm-based and cold-based part of the glacier is also identifiable.

Part II – Summer 2009

Summary

An extensive, multi-component, geophysical dataset has been acquired at the glacier Storglaciären, Northern Sweden, during 62 days in summer 2009 (July–September). The field season was primarily funded by the National Geographic Society (grant #8647-09) and other sources including Stockholm University, Swansea University, BIM Adda and Percy Sladen Memorial Fund. The number of person/days in the field was 160. The field team was based at the Tarfala Research Station, one hour on foot from the glacier. The field season was enormously facilitated by the good weather, which allowed almost daily data collection on the glacier. The main aim of the season

was to discriminate spatially the water distribution with depth at different sites on the glacier. We undertook borehole radar and seismic surveys in three locations: lower ablation area, upper ablation area and at approximately the equilibrium line. A borehole seismic experiment was undertaken at one location in boreholes ~30 m deep in the upper ablation area. At each site we collected at least two radar surveys in two different pairs of boreholes, ~100 m deep. Further information about the drilling sites was obtained using surface common-offset ground-penetrating radar (GPR) surveys. The total number of deep (> 80 m) boreholes drilled was 14. During the campaign we used a borehole radar system, a seismic sparker powered by a high-voltage unit, and hydrophone string to record seismic waves, a surface GPR system, an inclinometry tool, a differential GPS system and a hot-water drill to drill the boreholes. In this report we discuss scientific background, logistics, field methodology and preliminary results of the campaign.

Fieldwork and research

We originally planned to conduct multi-component experiments: radar and seismic zero-offset-profiling (ZOP) at as many sites as possible on the glacier. In these experiments a geophysical signal (radar or

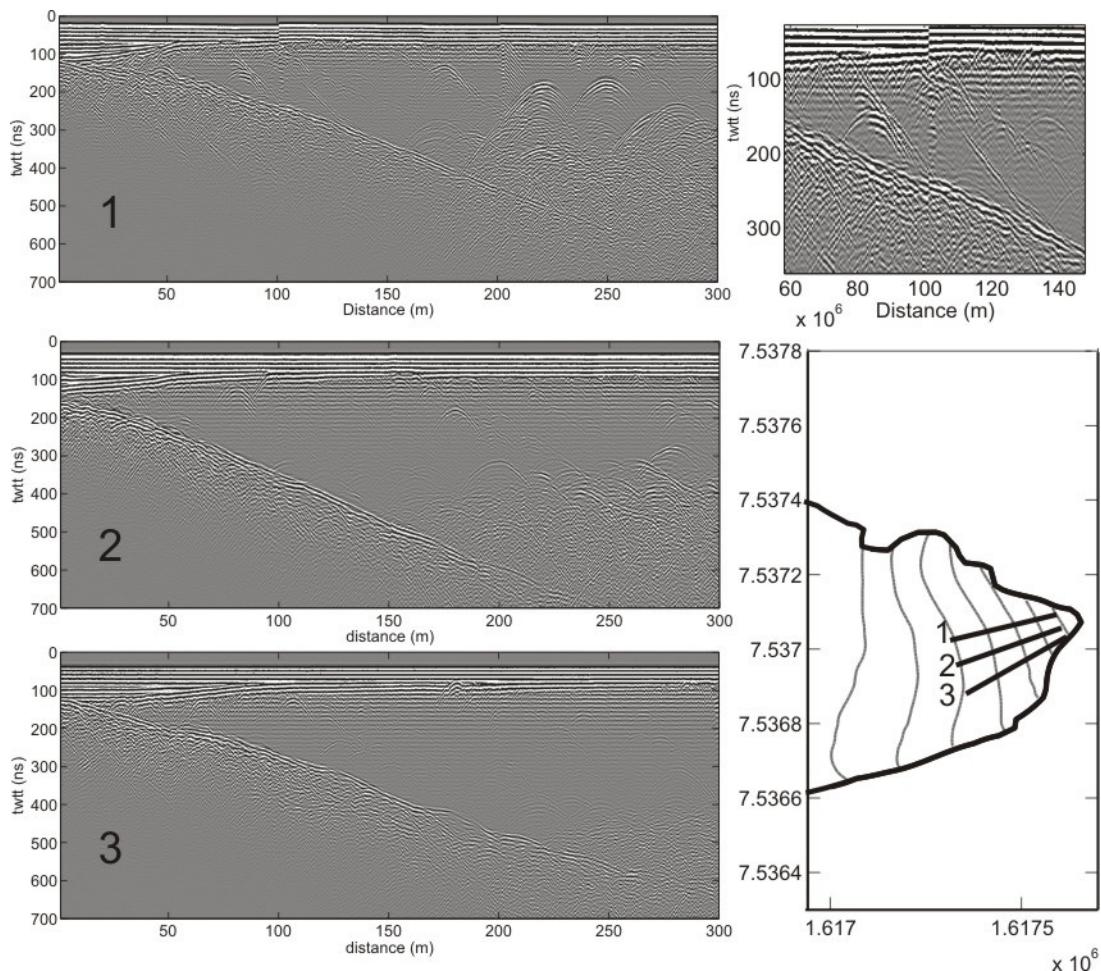


Figure 6. 100 MHz CO lines collected at the terminus, clear reflectors dipping up glacier are shown in the northern profile.

seismic) is generated at known depth in a borehole and recorded (by a radar antenna or a seismic phone) at the same depth in an adjacent borehole; the travel time of the signal between the inter-borehole region is therefore measured. Since propagation speed is related to water-content measurements of this parameter allow calculation of water. Undertaking such multi-component experiments is far from easy. In fact the data can be successfully acquired only if all the following steps are achieved:

- a) Two boreholes, wide enough to be instrumented, are drilled in the glacier. Typically our boreholes were 10-15 cm wide and of variable depth, depending on the site. The maximum depth we drilled was 130 m (presumably the bed at site B, see Figure 7). On average we drilled not further than 100 m at site B and site D. Ice thickness at site A was less than 100 m and therefore drilled only to 80 m and this site.
- b) Both boreholes have to be water-filled. Whereas this condition is advisable for the radar (better antenna coupling) it is strictly necessary for the seismic experiment since the signal is generated by a sparker that can deafen people if fired in air and the signal is recorded using a hydrophone that does not work in air.
- c) The geometry and the spatial orientations of both boreholes are accurately surveyed using an inclinometry. Boreholes, especially at depth, can deviate considerably from the vertical and inclinometry measurements are critical for

interpreting the survey.

- d) A ZOP radar profile is collected in the pair of boreholes.
- e) A ZOP seismic profile is collected in the pair of boreholes.
- f) The top of each hole is located accurately using a differential GPS system. Since the objective of the survey is to precisely measure the geophysical signal's propagation speed it is necessary to reduce significantly the errors in measuring distance.

The equipment and the hot-water drill were lifted onto the glacier on the 5th of September and the initial operations for starting the drilling started immediately after. We used TRS hot-water drill system, composed of a pump which gathered supra-glacial running water into a boiler, the heated water (around 90°) is then pressurized and redirected by a system of rubber hoses into a metal end (~1.5 m height) which is the actual drill. An unexpected failure of the pump engine during preliminary tests caused a two weeks delay in the drilling operations. We therefore undertook common-offset surface radar measurements on site A during this time. A dense grid of radar lines (50 m long) was acquired in order to understand and explore Storglaciären thermal and hydrological regime. (The surface-radar dataset will add to the detailed surface radar campaign undertaken by A. Gusmeroli and P. Jansson during spring 2009; that work explores the recent evolution of Storglaciären's thermal regime after the recent thinning of the cold ice observed by Pettersson et al., 2003).

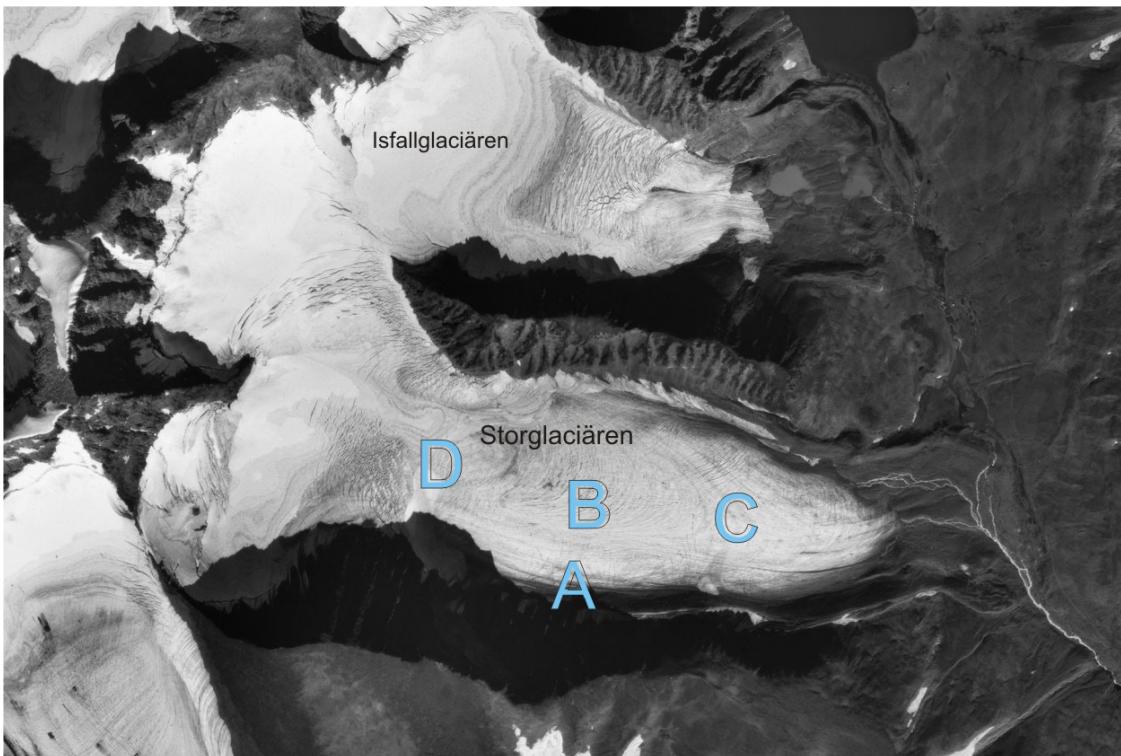


Figure 7. Summer aerial photo of the Tarfala valley with indications of the areas investigated in summer 2009.

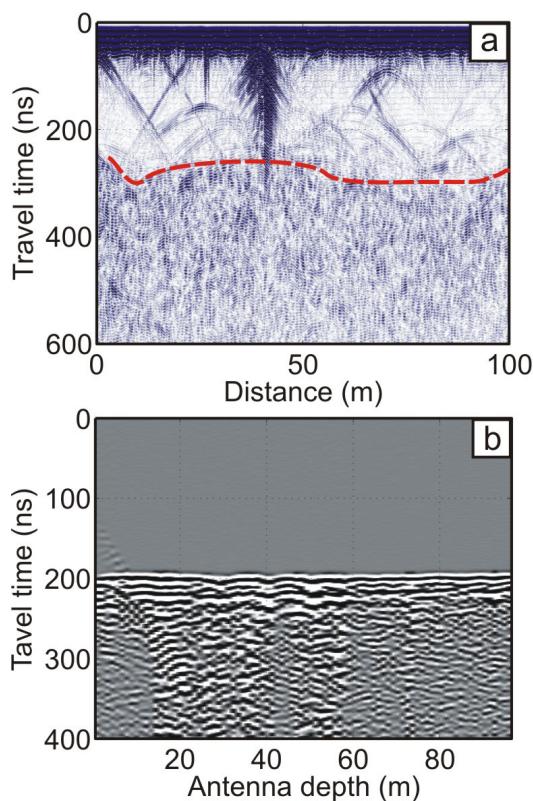


Figure 8. Data samples. (a) surface common offset radar; (b) borehole zero offset radar profiles.

Drilling at site B started on the 29th July. The first drilling-site (site B) was located in the upper ablation area of the glacier (Figure 7). In this area we undertook 80 m deep radar ZOP the summer 2008 (Gusmeroli et al., 2010b). By repeating the same experiment one year after we can understand if the glacier hydrological system is subjected to inter-annual temporal variations. At site B we successfully acquired multi-frequency, multi-azimuthal radar ZOP in boreholes that, for one survey, reached the bed, at ~130 m. At this site we also undertook seismic ZOP experiments generating seismic waves using a high-voltage power supply connected to a borehole seismic sparker. The seismic signal was then recorded by a hydrophone string located in an adjacent borehole.

After the multi-component seismic-radar experiment was acquired, the seismic equipment (which was hired) had to be shipped back to the UK and the rest of the campaign was focused on exploring different hydrological regimes on the glacier by moving sites. We therefore packed and prepared for transport all the equipment left on the ice. The new site (site C) was chosen to be located just below the “riegel”, a transverse bedrock-ridge beneath Storglaciären which is known to play an important role in the dynamics of the glacier. At site C (started on the 8th August) we undertook extensive drilling, multi-frequency, multi-azimuthal, multi-location ZOP radar. Site C was

cleaned on 22nd August, drill, fuel and equipment were packed again for the last movement of the season.

The last site was located just below the accumulation area (site D, Figure 7). At this location ice flow is particularly high and the ice surface was still covered by slush. As in the previous sites extensive drilling with boreholes up to 120 m and detailed ZOP radar profiles were collected. It was notable that boreholes drilled at site D closed in less than two days, a clear signal that ice velocities in the last site were much higher than those the other two sites (one borehole at site A was used for almost 6 days. We never observed borehole closure by ice-deformation at sites B and C; whereas at site D we noticed that the ~5 cm wide antennas lowered in boreholes just after drilling could not be lowered in the same boreholes the day after. However a sufficient number of ZOPs were acquired also at Site D. Then on the 1st of September we started packing the equipment and cleaning site D. Equipment was finally removed from the glacier on the 4th September. The last few days were used to fully clean the sites (e.g. from empty jerrycans), pack the equipment and clean the boiler of the drill at TRS.

Data sample

In Figure 8 we show two examples of the data we collected: a surface radar profile with indication of the boundary between the upper cold and the lower warm ice (Figure 8a) and a borehole radar profile (Figure 8b). Only preliminary results can be given at this stage since the field season has just ended.

Data summary

SITE	DATA COLLECTED
A	15x50m surface radar lines (example in Fig. 8a)
B	4x100m long surface radar lines; 7 bore-hole radar profiles (example in Fig. 8b); 1 seismic profile
C	4x50m long surface radar lines; 6 borehole radar profiles
D	5 borehole radar profiles

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