GLACIOLOGY IN THE KEBNEKAISE MASSIF, NORTHERN SWEDEN. REPORT OF THE SPRING 2009 GEOPHYSICAL FIELD SEASON

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Abstract

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 whitin 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, which we believe will bring many improvements on the current understanding of glacier geophysics, glacier hydrology and glacier dynamics.

Contents

Chapter 1

Introduction

1.1 Glaciological research in the Kebnekaise massif

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. It occupies the northern area of the Scandinavian Mountains, a mountain range that runs through the Scandinavian Peninsula, geologically related to the mountains of Scotland, Ireland and the Appalachian Mountains of North America. 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 within the category of *small glaciers*. These fast retreating ice masses are contributing the majority of the 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.

Glaciological research in the Kebnekaise area started just after the end of the second world war (see Holmlund and Jansson (2002) for further information). In 1945, the first mass balance measurements were performed on Storglaciären; since then the mass balance of the glacier (both winter and summer balance) has been measured annually with direct

Figure 1.1: *Kebnekaise massif seen from Tarfala valley. Heavily crevassed parts of the Kebnepakte glacier and its frontal moraine system are visible. photo AG - April 2009*

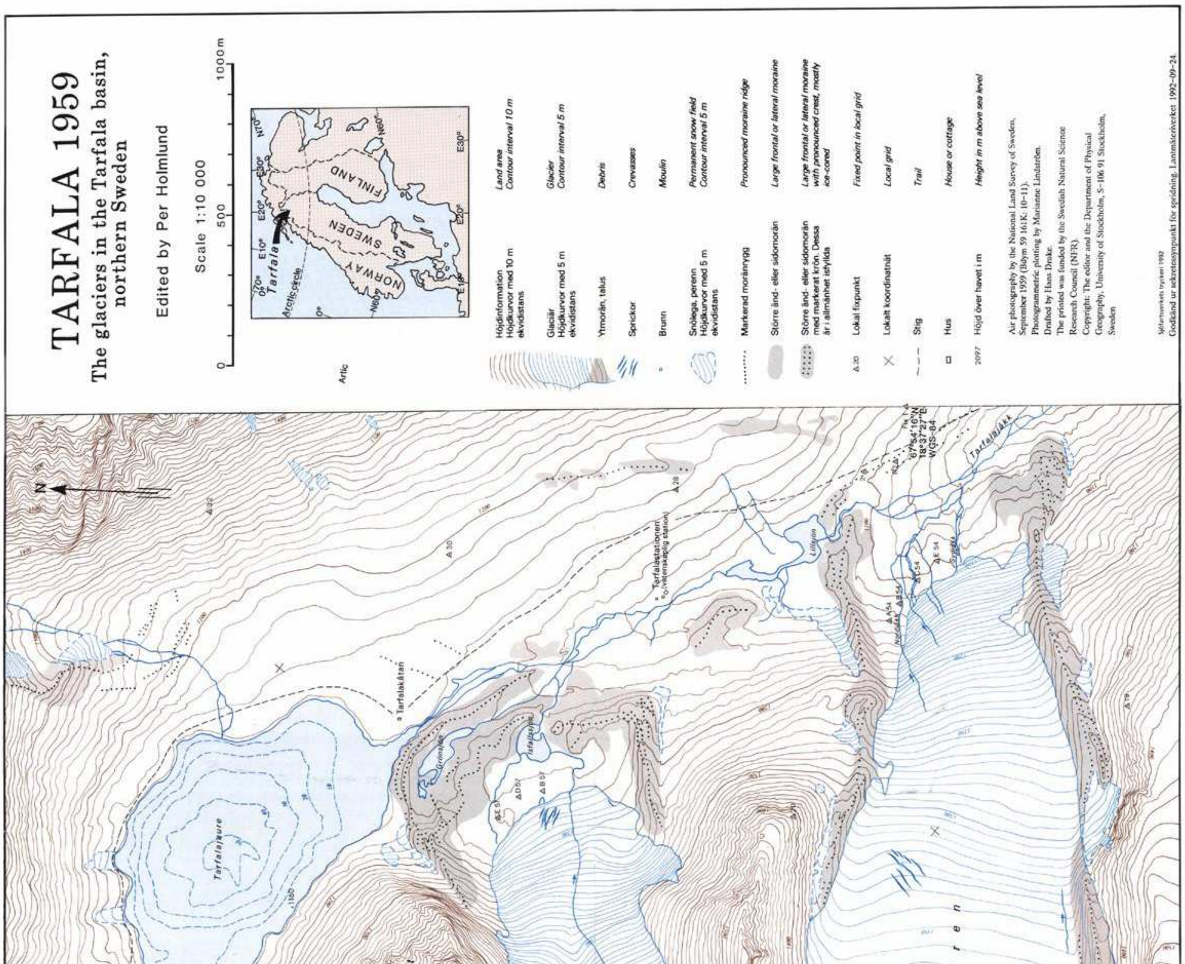

Figure 1.2: *Map of the area*

glaciological techniques. The Storglaciären mass balance series has become recognized worldwide as an important record of the relationship between ice mass variations and climate. The series is cited in all the main glaciology text-books, and the mass balance methods used today as international standard methods were, to a great extent, developed at Storglaciären. Throughout the years several generations of glaciologists have been able to integrate this knowledge with many other aspects of glaciology, including nivology, meteorology, hydrology, climatology, palaeoclimatology, thermodynamics, permafrost, dynamics and sedimentology making Storglaciären one of the best studied glaciers on the entire planet. For our field-team, it has been a pleasure and an honour to undertake research on this glacier.

1.2 Tarfala Research Station

Stockholm University's Tarfala Research Station was the base of our field season. The station is located at 67°55'N, 18°35'E in the Tarfala valley, at the foothill of Kebnekaise's east side. The valley is a typical sub-arctic high-alpine area between 800 and 2114 m a.s.l. and hosts six glaciers. The research station offered accomodation, food, internet connection, warm rooms where clothes and equipment could be dried, and electricity for battery recharging. The station is only half hour's ski from the terminus of Storglaciären (1150 m a.s.l.), one hour ski from its lower ablation area (1400 m a.s.l.) and 90 minutes from the two accumulation basins of the glacier (1500-1600 m a.s.l.).

1.3 Scientific background of the expedition

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 behavior 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

Figure 1.3: *Tarfala Research Station in the Tarfala valley - photo AG April 2009*

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 (see Murray *et al.* (2007) and Gusmeroli *et al.* (2008)) for further information), which is exploring 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 contnet. Improvement in the knowledge that we have on this topic will represent a valuable step forward in many important processes in glaciology such as:

- 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 evidence has, however, never been observed in the field, and a validation of the current theories is needed.

- 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.

- 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.

1.4 Glacier geophysics

In this project we use artificially generated geophysical signals, such as electromagnetic and seismic waves, to explore glacier properties. These techniques have been widely used by glaciologists in the last 40 years in order to measure ice thickness of ice sheets (e.g. Drewry (1983), understand their basal conditions (e.g. Blankenship *et al.* (1986) and Smith *et al.* (2005)), and their hydrological regime (Fountain *et al.*, 2005). Since direct investigations are logistically challenging and often simply *not possible* these methodologies are becoming part of the glaciological field science.

In radar measurements measurements the transmitted electromagnetic signal travels within the ice and is reflected back to the receiver when a material with different electrical properties (e.g. water, air, rocks) is encountered, this process allows the imaging of water bodies within the glacier. During seismic surveys, elastic energy is first propagated into the ice using a mechanical source (e.g. sledgehammer, shotgun) and then recorded once it travels back by the means of several receivers (geophones). All the measurement-points have to be located spatially by using a GPS.

Figure 1.4: *Radar survey at Storglaciären photo MF - April 2009*

Chapter 2

Fieldwork and research

2.1 Expedition members

The full list of people involved in the fieldwork was:

Member	Affiliation	Role
Alessio Gusmeroli	Swansea University	Expedition leader
Riccardo Scotti	Glaciological Service of Lombardy	Field scientist
Marco Fransci	Glaciological Service of Lombardy	Field scientist
Daniel Hjelm	Norbotten County	Field scientist
Tatjana Enzinger	Swansea University	Field scientist
Prof Peter Jansson	Stockholm University	Scientific supervisor
Christian Helanow	Tarfala Research Station	Field scientist
Henrik Tornberg	Tarfala Research Station	Station's superintendent
Prof Tavi Murray	Swansea University	Scientific supervisor

Numbers actually of people working on the glacier fluctuated throughout the season. After the initial input of one person (AG) numbers increased and field assistants alternated in the 30 days of data collection. The maximum number at any one time collecting data on the glacier (not including Tarfala Research Station) was three (AG,RS,MF). The first day of data collection was the 25 March and the equipment was removed from the glacier on the 22 of April. In those 30 days for 5 days we did not collect data (1 day of rest on Easter day, and 4 days of bad weather). After the equipment have been removed from the glacier AG spent 2 more days in the field for GPS measurements and cleaning up the glacier from survey stakes planted in the snow increasing the total of days in the field to 27. The number of person/days in the field was 48. A schematic diagram of the persons alternating in the field is given in figure 2.1.

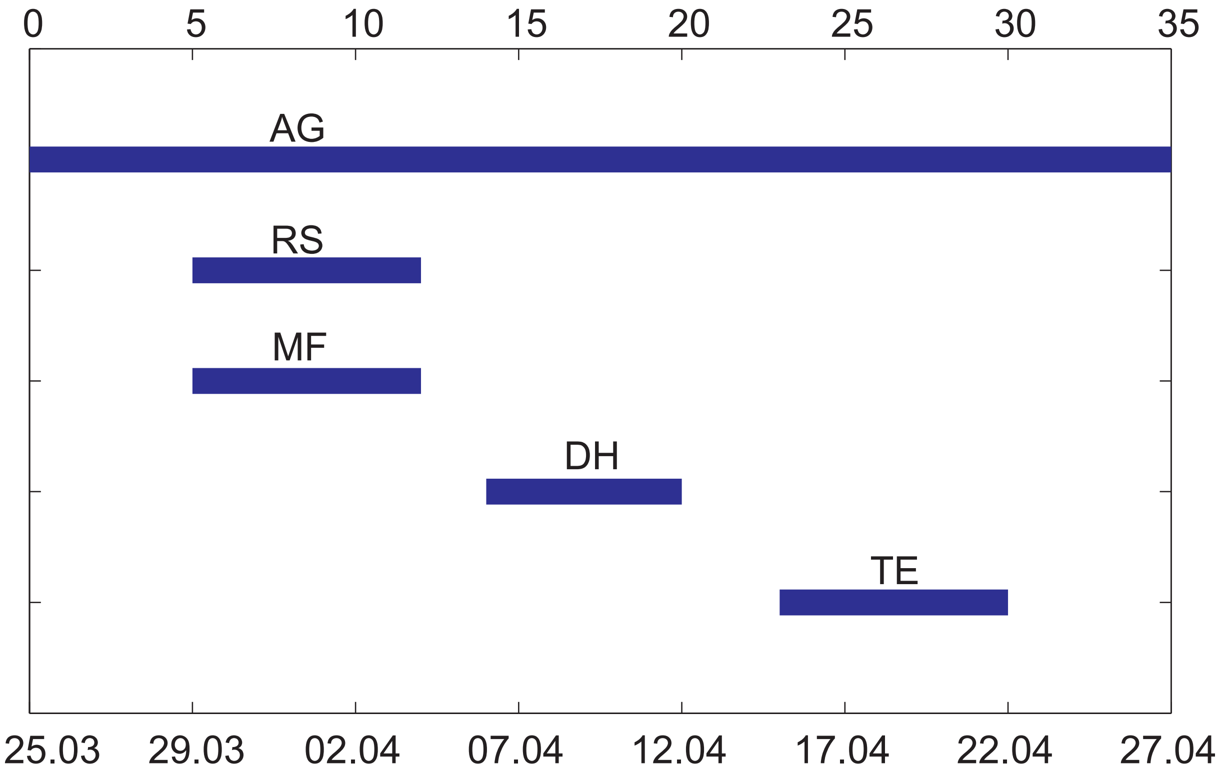

Figure 2.1: *Personnel occupation during the field season.*

2.2 Field research aims

To contribute in the achievements outlined in section 1.2 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 beacuse 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 logistically less challenging (not least for shipping costs) to focus in obtaining a robust dataset using one technique only.

The main field area targetted 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. Results of this first field season together with radar surveys collected during the spring 2009 season are now part of a manuscript which we hope to submit to the Journal of Geophysical Research (Gusmeroli *et al.*, 2009).

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.

- Collaborate with P. Jansson and R. Pettersson in 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's 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 $\sim$ 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 informations about relatively unknown areas of Storglaciären (e.g. the terminus and the accumulation area). These surveys can also be use to locate future drilling spot by identifying potential study areas.

2.3 Field logistics

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 (see figure 2.3).

2.4 Study area

We concentrated the radar measurements in three different part of the glacier (see figure 2.3):

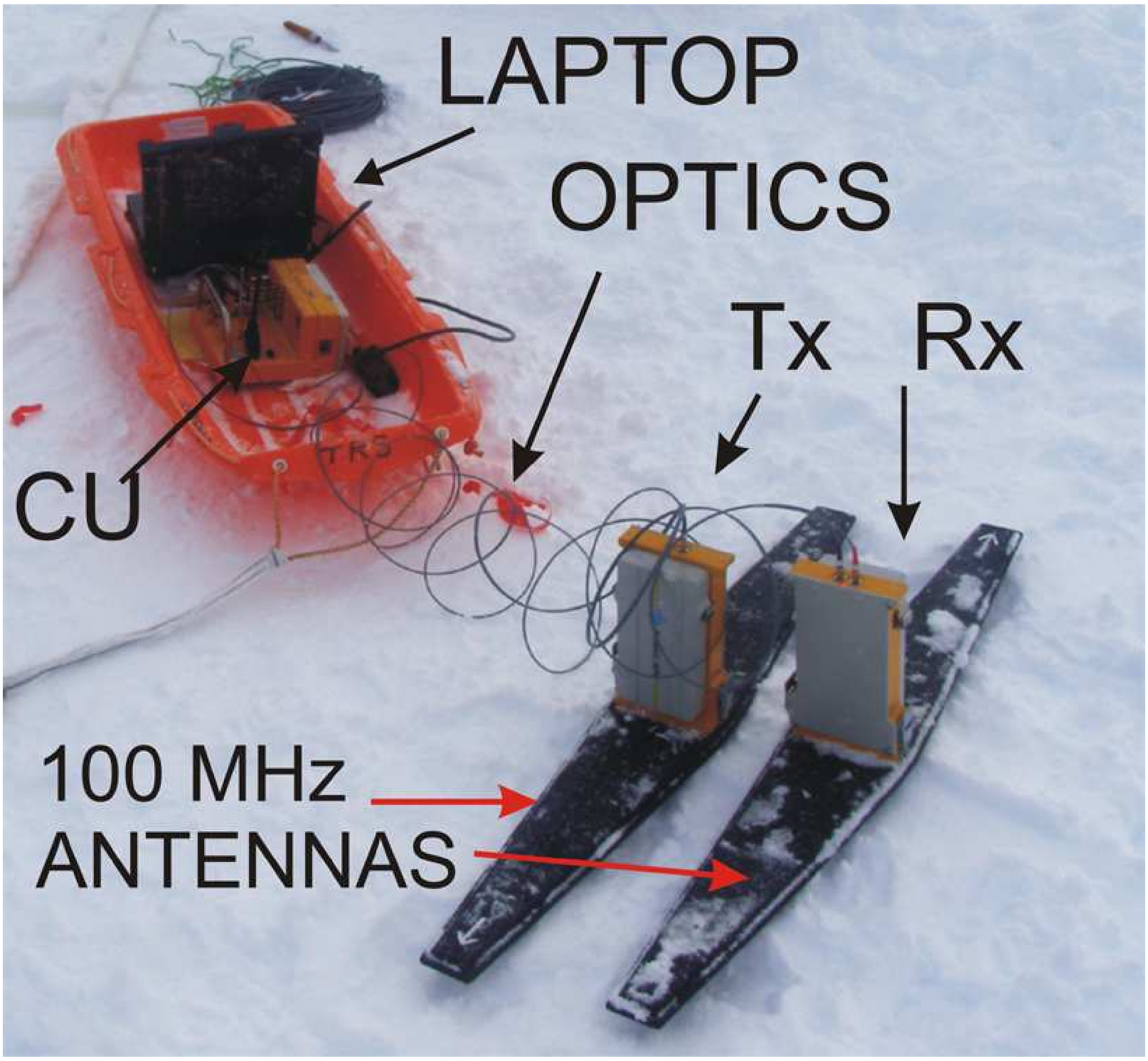

Figure 2.2: *The radar system that used in the data acquisition. Tx, transmitter; Rx, receiver; CU, control unit*

- *(A)*: The upper ablation area of the glacier located approximately at 1350 m of elevation. This area were extensively investigated by borehole geophysical surveys in the summer. In *(A)* the glacier is polythermal and a $\sim$ 20-25 meters thick cold suface 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 mantaining the ice temperate.

2.5 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's englacial water system and glacier dynamics (see figure 2.4 for a map of the experiments); whereas a detailed network of GPR surveys constitues the monitoring-mapping part (see figure 2.6).

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

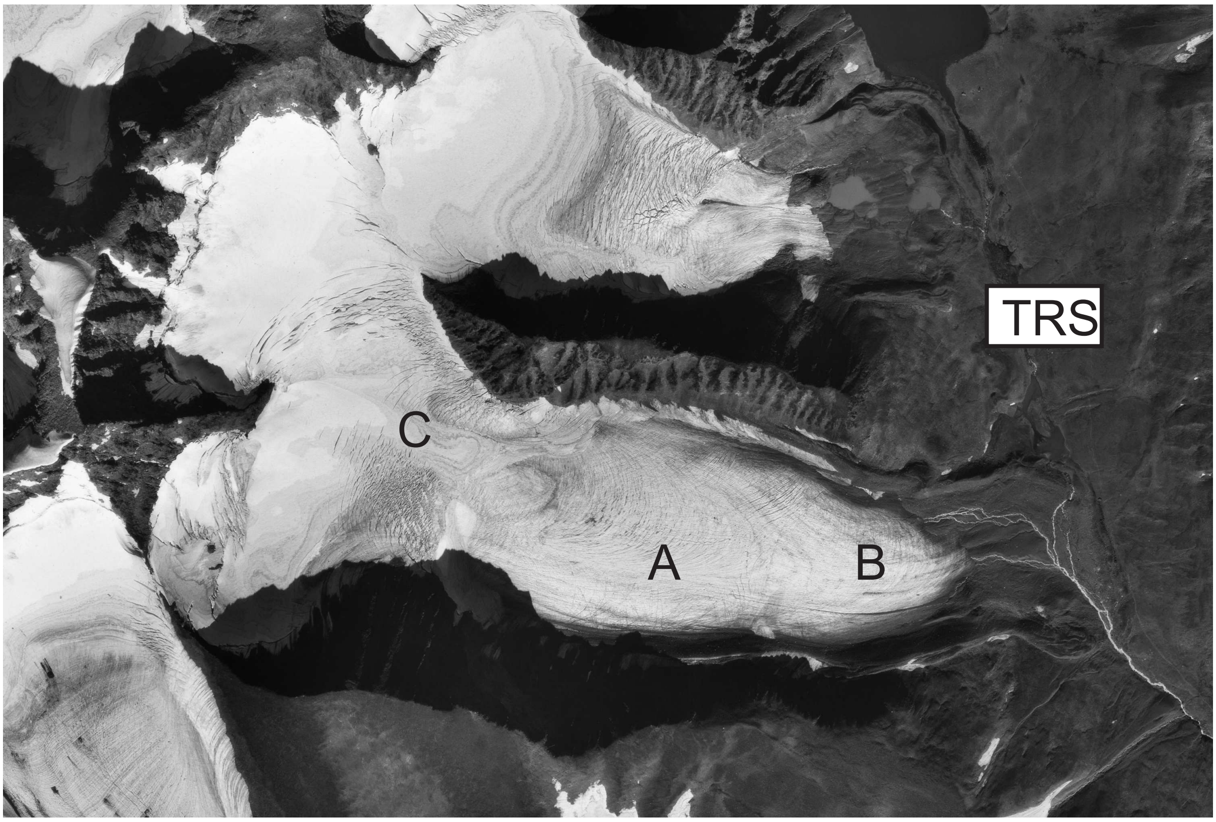

Figure 2.3: *Summer aerial photo of the Tarfala valley with indications of the areas investigated. A: upper ablation area, B: terminus, C: accumulation area. TRS: Tarfala Research Station.*

line using 16 different polarisations (orientations of the 100 MHz antennas - see figure 2.5). This means that the survey lines indicated with red color in figure 2.4 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 2.4) 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 2.4).

- 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 2.4. 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 (N,S,E,W).

A detailed mapping of the polythermal structure of the glacier have also been performed togheter with the Swedish colleagues using 100 MHz CO surveys (see figure 2.6).

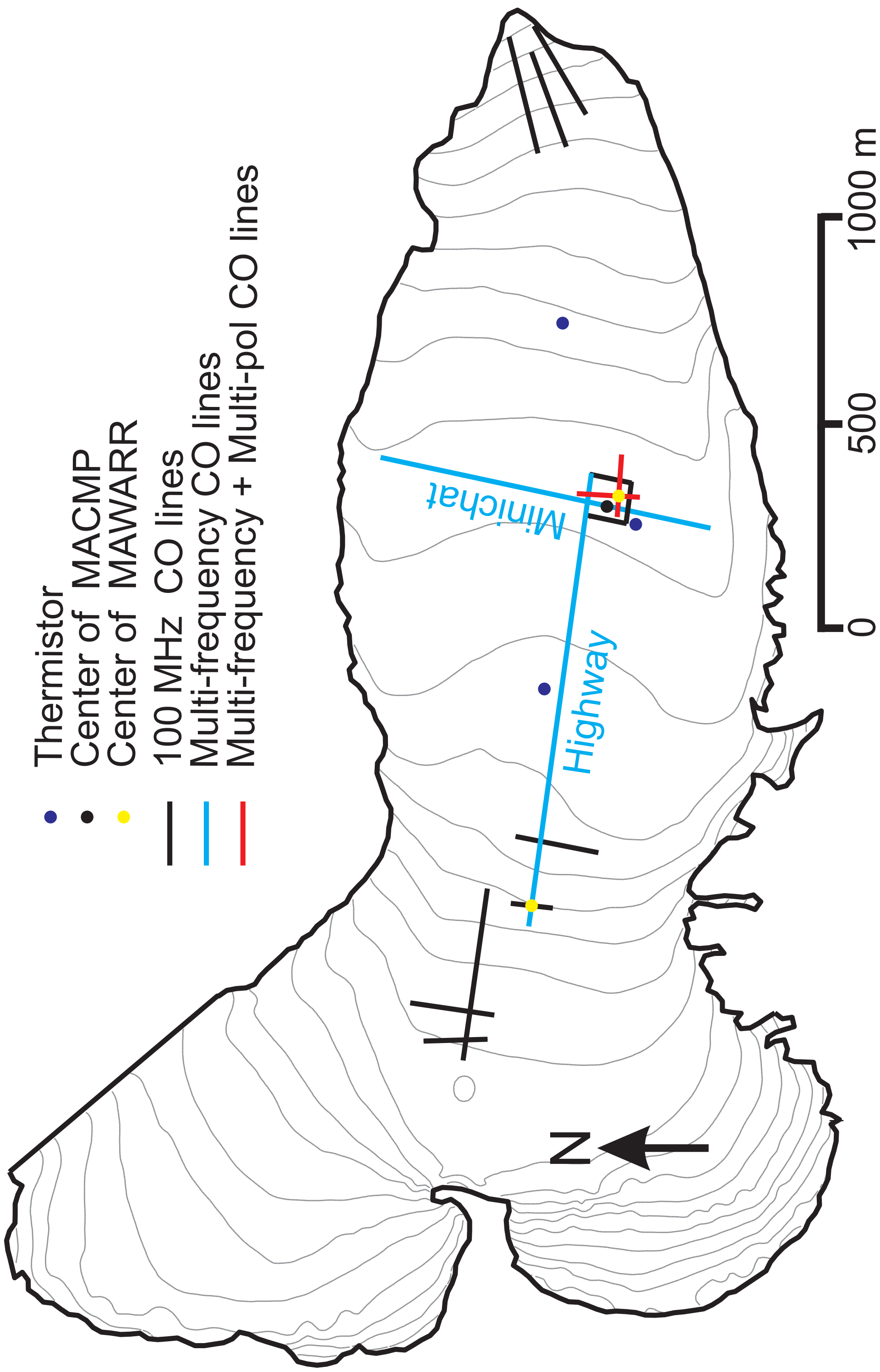

Figure 2.4: *Map of the surveys*

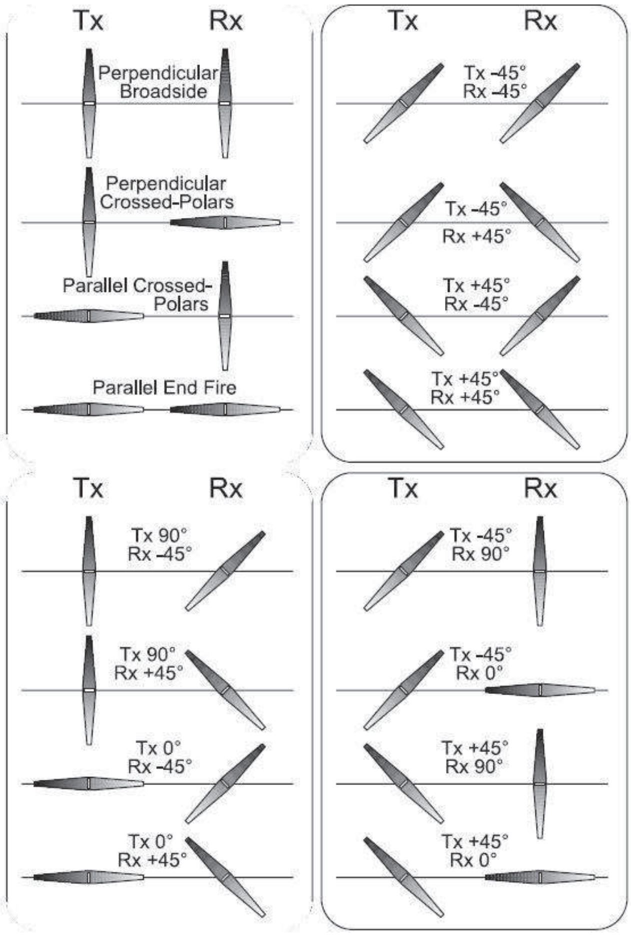

Figure 2.5: *Sixteen polarization components wer collected at 100 MHz using combination of four orientation direcions. The figure is from Barrett and others, 2009.*

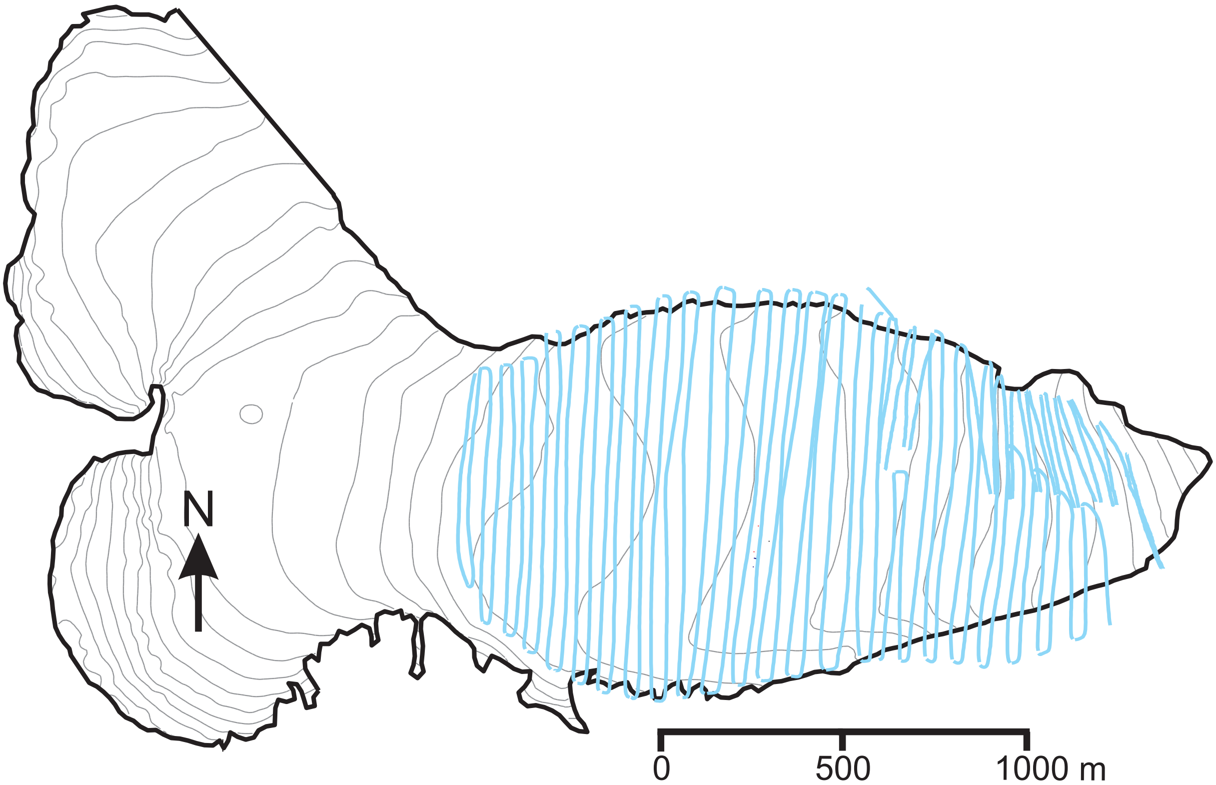

Figure 2.6: *The mapping of the polythermal structure of the glacier was done with several 100 MHz profiles. The dataset show in this figure was mainly collected by P. Jansson and is part of Jansson and R. Pettersson's recent research (Pettersson* et al.*, 2003) on polythermal glaciers.*

Chapter 3

Preliminary results

In this section we show some examples of the data we collected. Only preliminary results can be given at this stage since the field season has just ended. We will integrate these first findings with more robust conclusions about Storglaciären's thermal state dynamics and englacial water system by submitting papers to international peer-reviewed journals such as *Journal of Geophysical Research*, *Geophysical Research Letters* and *Journal of Glaciology*. One manuscript which analyses the vertical variations in water content within the temperate ice of Storglaciären is already in preparation. A copy of future reports and publications will be also sent to the funding bodies.

3.1 CO surveys

Figure 3.1 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. A sample of the 100 MHz CO lines collected

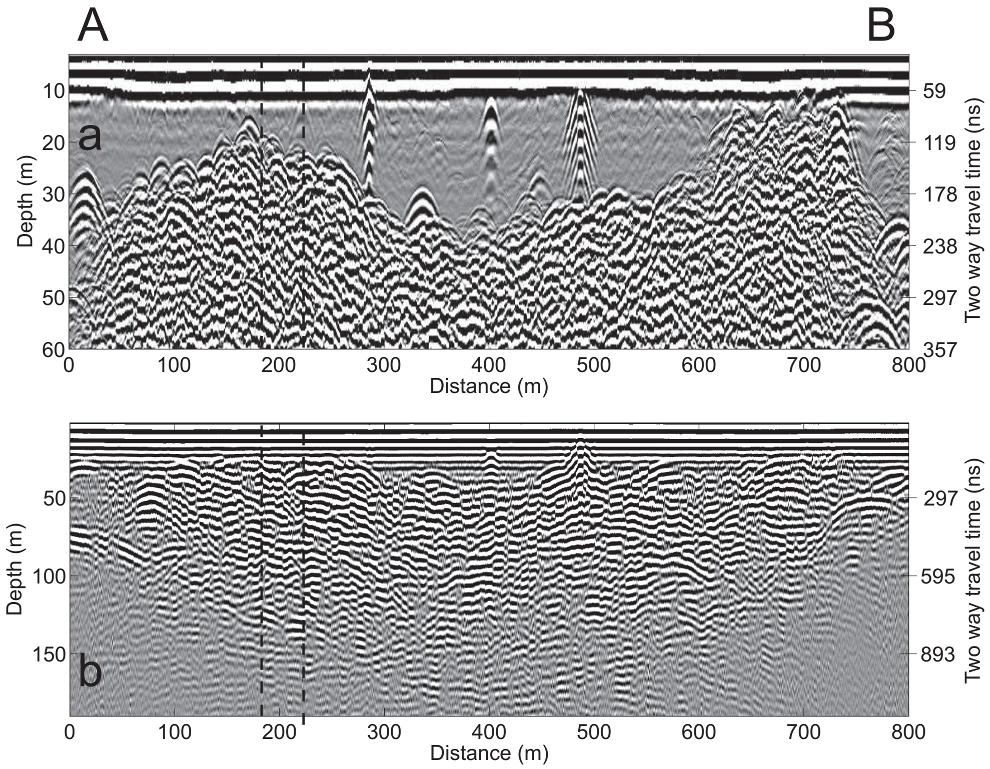

Figure 3.1: *25 MHz CO line Minicha, A and B represents the southern and the northern ends of the line respectively. The area in between the two dashed lines is the area investigated in the summer. a) unprocessed radargram used to measure the thickness of the cold surface layer. b) low-pass filtered 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.*

at the terminus is also shown (Figure 3.2). 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.

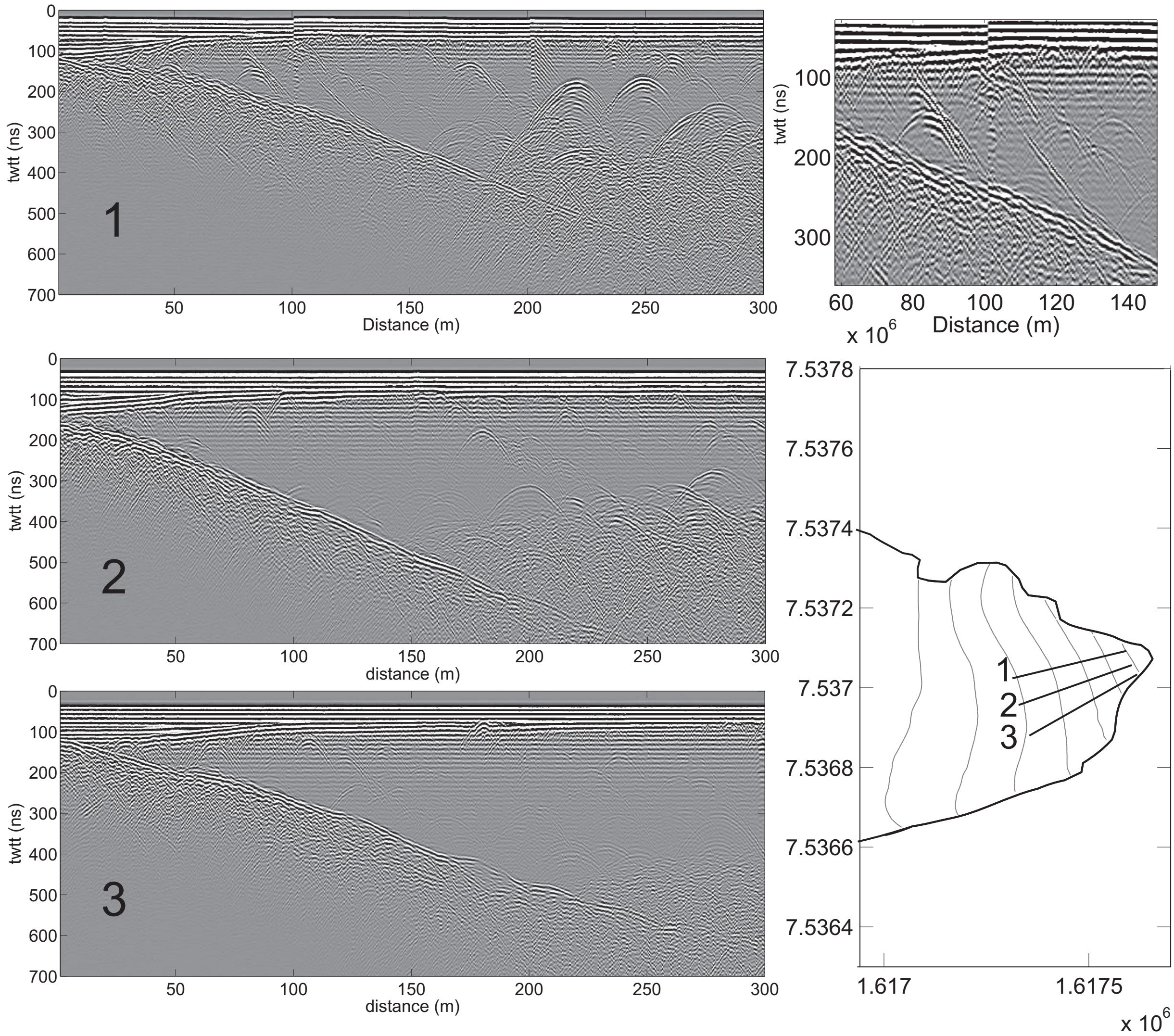

Figure 3.2: *100 MHz CO lines collected at the terminus, clear reflectors dipping up glacier are shown in the northern profile.*

Chapter 4

Photos

Figure 4.1: *The sleeping house at Tarfala Research Station - Photo AG, April 2009*

Figure 4.2: *Tarfala Reseach Station seen from the western side of Tarfala valley - Photo AG, April 2009*

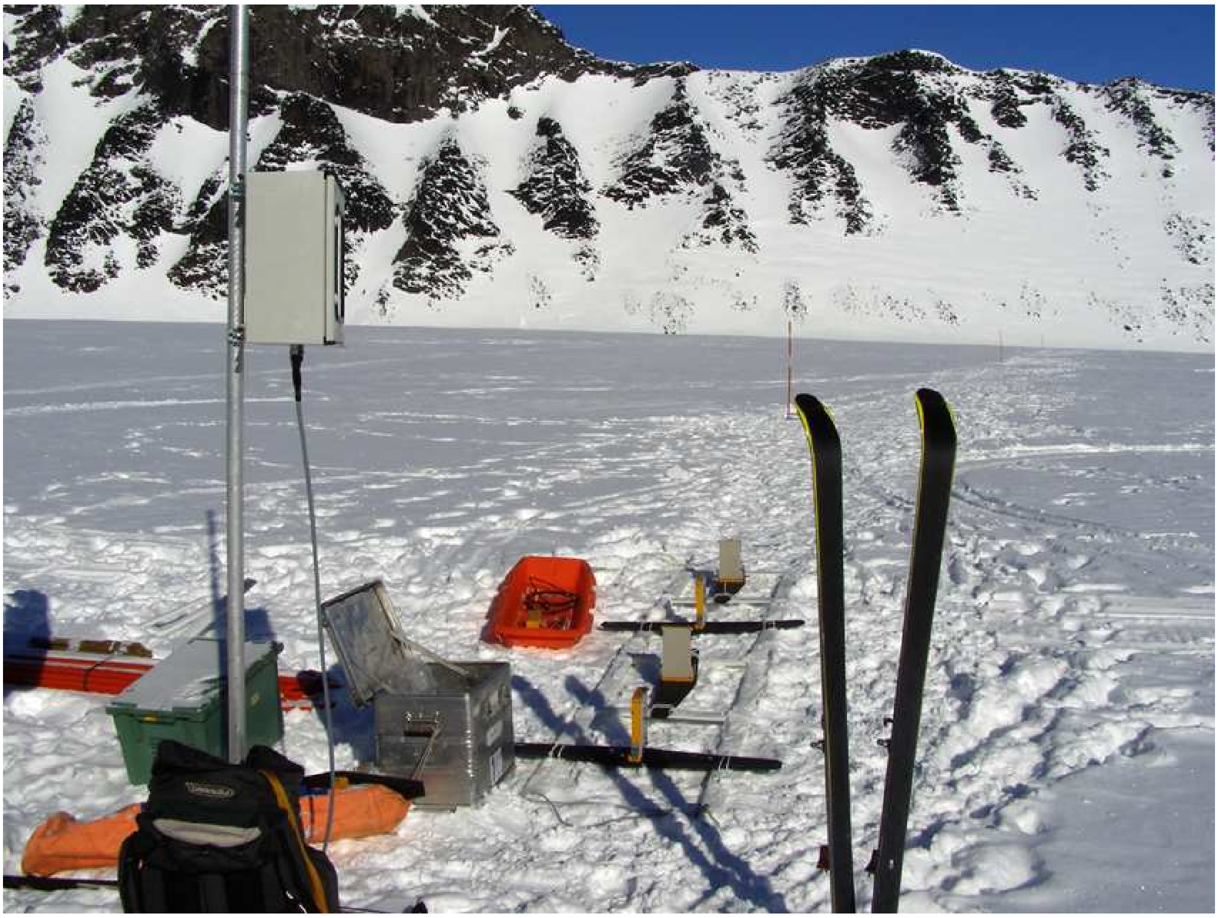

Figure 4.3: *The start of a field day on Storglaciären, the radar system at the survey area - Photo AG, April 2009*

Figure 4.4: *Moving with ski on Storglaciären - Photo AG, April 2009*

Figure 4.5: *The field team at the end of the radar line Highway - Photo AG, April 2009*

Figure 4.6: *Ski traces from the field team on the way down from the glacier to the station - Photo AG, April 2009*

Figure 4.7: *Storglaciären and the eastern side of Kebnekaise, Sweden's highest mountain - Photo AG, April 2009.*

Figure 4.8: *Preparation of a radar CMP survey on the glacier - Photo AG, April 2009.*

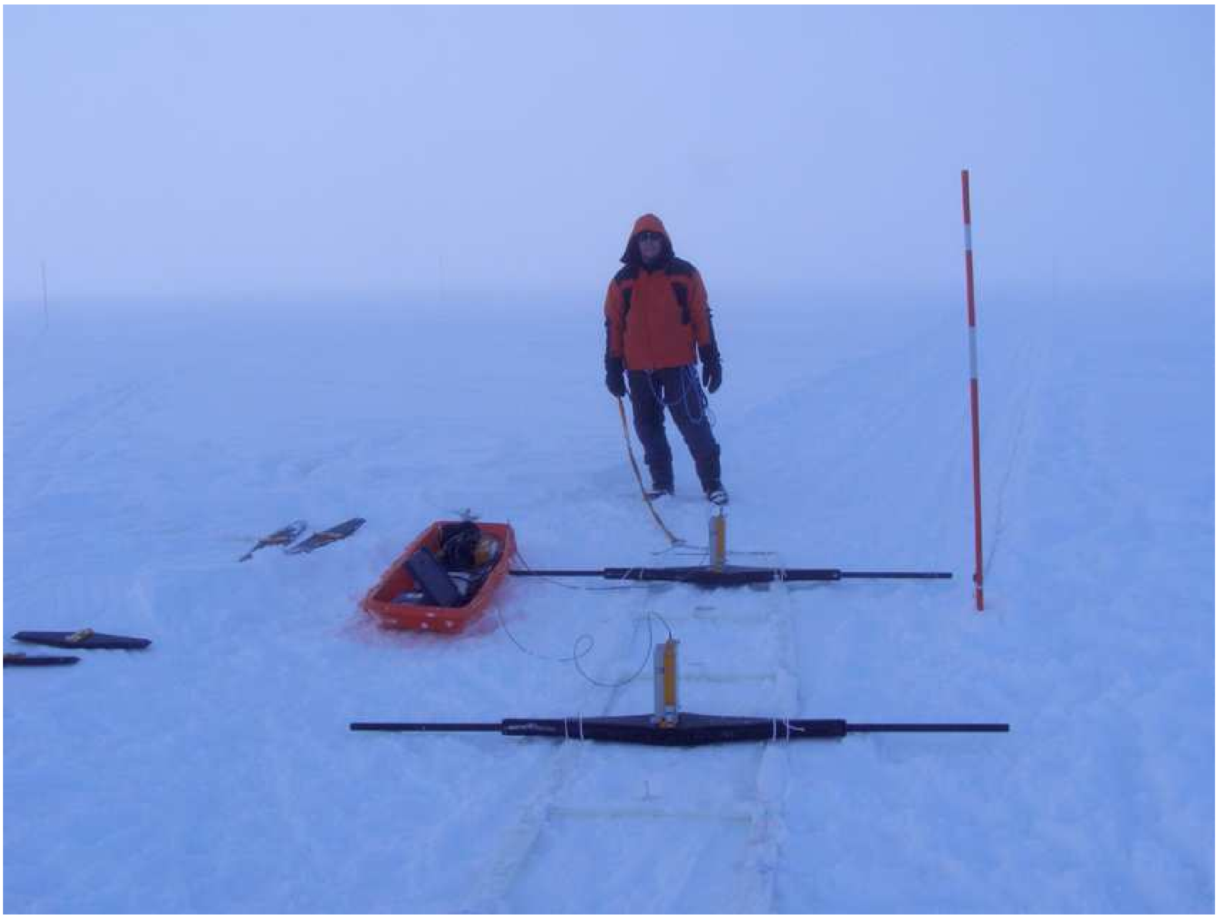

Figure 4.9: *50 MHz radar survey on the glacier - Photo AG, April 2009.*

Figure 4.10: *Rounded mountains south from Tarfala valley - Photo AG, April 2009.*

Figure 4.11: *Moving with ski in Tarfala valley - Photo AG, April 2009.*

Figure 4.12: *Tarfala valley from the north - Photo AG, April 2009.*

Figure 4.13: *Moraine systems of Storglaciären and Isfallglaciären - Photo AG, April 2009.*

Figure 4.14: *Scandinavian mountains from the top of Kaskasatjakka (2076 m) - Photo AG, April 2009.*

Chapter 5

Acknowledgements

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Chapter 6

Financial breakdown

Source	Amount in GBP
JWC	1000
BIM	879
PSF	750
MEF	600
BSG	450
QRA	350
ES	200
TOTAL	4179

Table 6.1: Money available for the expedition - JWC: Jeremy Willson Charitable Trust; BIM: Consorzio dei Comuni del Bacino Imbrifero Montano dell'Adda; PSF: Percy Sladen Fund; MEF: Mount Everest Foundation; BSG: British Society for Geomorphology; QRA: Quaternary Research Association; ES: Earth and Space Foundation

	Amount in GBP
TRS bill	2853
Shipping costs	900
Trips	600
TOTAL	4368

Table 6.2: Fieldwork costs, the TRS (Tarfala Research Station) bill includes accomodation, food and transport costs in Tarfala

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