

**POLYTHERMAL GLACIER
STUDIES IN SVALBARD
DETERMINED BY GROUND-
PENETRATING RADAR**

**ANJA
PÄLLI**

Department of Geosciences,
University of Oulu

OULU 2003



ANJA PÄLLI

**POLYTHERMAL GLACIER STUDIES
IN SVALBARD DETERMINED BY
GROUND-PENETRATING RADAR**

Academic Dissertation to be presented with the assent of
the Faculty of Science, University of Oulu, for public
discussion in the Auditorium GO101, Linnanmaa, on
November 15th, 2003, at 12 noon.

OULUN YLIOPISTO, OULU 2003

Copyright © 2003
University of Oulu, 2003

Supervised by
Doctor John Moore

Reviewed by
Doctor Yuri Macheret
Assistant Professor Cecilia Richardson-Näslund

ISBN 951-42-7177-7 (URL: <http://herkules.oulu.fi/isbn9514271777/>)

ALSO AVAILABLE IN PRINTED FORMAT

Acta Univ. Oul. A 406, 2003

ISBN 951-42-7176-9

ISSN 0355-3191 (URL: <http://herkules.oulu.fi/issn03553191/>)

OULU UNIVERSITY PRESS

OULU 2003

Pälli, Anja, Polythermal glacier studies in Svalbard determined by ground-penetrating radar

Department of Geosciences, University of Oulu, P.O.Box 3000, FIN-90014 University of Oulu, Finland
Oulu, Finland
2003

Abstract

The overall aim of this Thesis is to emphasise how Ground Penetrating Radar (GPR) can be used in different glaciological studies: in mapping the inner structure, determining accumulation rates, estimating water contents, mapping drainage channels and superimposed ice. The Thesis also aims to improve current knowledge on Svalbard polythermal glaciers: their hydrothermal properties, drainage and behaviour in the changing climate.

Six glaciers were studied: four tidewater glaciers, one ice-field and one valley glacier. The hydrothermal structure of Hansbreen was mapped with GPR at high lateral and vertical resolution. The hydrothermal structure of the glacier is highly variable and complex. In general the temperate ice contains 1-2% water, but water contents of about 4% are associated with englacial water channels or water-filled near surface crevasses or moulins. Hydrothermal properties determined from detailed GPR surveys of Hansbreen, Werenskioldbreen, Nordenskjöldbreen and Kongsvegen show similar structures such as foliations and superimposed ice in the firn-ice transition area, though with different emphasis on each glacier. The overall extent of superimposed ice was difficult to measure accurately because of the limited resolution and the sporadic nature of the reflections. However there is encouraging similarity between GPR and satellite imagery of superimposed ice extent. Hydraulic geometry models of the subglacial hydrology of Hansbreen and Werenskioldbreen suggest that the water pressure is generally close to ice-overburden pressure but varies greatly depending on local conditions.

GPR data and data from three ice-cores were used to determine spatial and temporal variation of snow accumulation on a longitudinal profile of Nordenskjöldbreen. Spatial variations of 40-60% in snow accumulation over short distances along the profile were observed. The results indicate a 12% increase in accumulation rate during the late 1980s and 1990s. Hornbreen and Hambergbreen and several surrounding glaciers in southern Svalbard were mapped with GPR together with a DGPS (Differential Global Positioning System) in 2000. The data were compared to glacier surface height and glacier front length data from 1936 and 1901. The results show that the low-lying glaciated valley filled with Hornbreen and Hambergbreen may become a partially inundated ice-free isthmus within the next 100-150 years.

Keywords: glacier recession, hydrothermal structure, radar sounding, spatial accumulation

Acknowledgements

The way to the end of this long “tunnel” has been heavy but very challenging and interesting. I have learnt a lot on the way and have had a magnificent possibility to live some of my dreams true. However without numerous people help and support I would not have survived.

I am very grateful for my supervisor Dr. John Moore for the trust and great flexibility he has shown during these years. He has introduced me to the fascinating world of glaciology and gave the great opportunity to work in Svalbard. He has given me advice and good criticism with my work and has helped always when I have asked for it. He also introduced me to the Nordic and European glaciological communities. I would like to thank Dean Jacek Jania and Prof. Piotr Glowacki for the great co-operation in Svalbard and in Poland. I am very thankful for Dr. Elisabeth Isaksson and Dr. Jack Kohler for their support and help every time needed and with the manuscripts. I wish to thank also Dr. Veijo Pohjola and Dr. Leczek Kolondra for collaboration and advice.

I wish to thank my professor Sven-Erik Hjelt, who has supported strongly my work in the field of Arctic Glaciology and helped with practical problems. I thank you the Head of the Graduate School Prof. Matti Leppäranta and all my colleagues in the Graduate School of Snow and Ice for their helpful comments and support. I am very grateful for the Head of the Physics Department Prof. Reino Laiho who kindly gave me the opportunity to do my work in one of the Wihuri Physics laboratory offices. I have felt very welcome while working here and I wish to thank warmly all my colleagues in Wihuri Physics Laboratory for their support.

Special thanks for M.Sc. Anna Sinisalo. You have not only been a colleague but a great friend and support in all troubles, in dark and happy moments during these years. I am also grateful for all my friends and numerous colleagues around the world for your help and support.

I want to give special thanks for my parents and siblings for the enormous support and of reminding me what is really most important in life. Finally I would like to thank you Janne for the greatest support. You have believed in my success with my work when times were tough for me. I thank you for the great patience and flexibility you have shown during the last months of this work and the humour you have brought to my life when days have been heavy at work.

This study was funded by the Finnish Academy and a grant from the Finnish Scientific Academy, the foundation of Vilho, Yrjö and Kalle Väisälä. The logistical support when working in Svalbard came from the Polish Academy of Sciences, University of Silesia, Poland and Norwegian Polar Institute. Thule Institute has supported the ground-penetrating radar system.

Oulu, May 2003

Anja Pälli

List of original articles

This thesis consists of this summary and the following five articles, which are referred to in the text by their Roman numerals.

- I Pälli A., J. Kohler, E. Isaksson, J. Moore, F. Pinglot, V. Pohjola & Samuelsson, H (2002) Spatial and temporal variability of snow accumulation using ground-penetrating radar and ice cores on a Svalbard glacier. *Journal of Glaciology* 48, 162: 417-424.
- II Pälli A., J.C. Moore & Rolstad C (2003) Firn-ice zone features of four polythermal glaciers in Svalbard seen by ground-penetrating radar. In press to *Annals of Glaciology* 37.
- III Moore, J.C., A. Pälli, F. Ludwig, H. Blatter, J. Jania, B. Gadek, P. Glowacki, D. Mochnecki & Isaksson E (1999) High-resolution hydrothermal structure of Hansbreen, Spitsbergen, mapped by ground-penetrating radar. *Journal of Glaciology* 45, 151: 524-532.
- IV Pälli A., J.C. Moore, J. Jania, L. Kolondra & Glowacki P (2003) The drainage pattern of two polythermal glaciers: Hansbreen and Werenskioldbreen in Svalbard. In press to *Polar Research*.
- V Pälli, A., J.C. Moore, J. Jania & Glowacki P (2003) Glacier changes in southern Svalbard 1901-2000. In press to *Annals of Glaciology* 37.

Papers I and III are reprinted from the *Journal of Glaciology* with permission of International Glaciological Society. Papers II and V are in press to *Annals of Glaciology* and included as Proofs to the Thesis with permission of the International Glaciological Society. Paper IV is conditionally accepted to *Polar Research*. In paper I, I processed and interpreted the radar data and GPS data, as well as did all calculations and writing except for the error chapter. In Paper II I collected the data from Hansbreen and Werenskioldbreen. I processed and analysed all the GPR data. The writing and figures were also done by myself. In paper III the general idea of the study is based to my Master's Thesis. I was responsible for all the GPR data collection and analysing, the calculations in table 1 and all the figures. In paper IV I did all the GPR surveys in the field, processing and interpretation, model runs, figures and writing. In paper V I collected all the GPR data, analysed it and the GPS data and collected data from the maps of Mission Russe. Calculations, interpretations, figures and writing was done by me.

Contents

Abstract	
Acknowledgements	
List of original articles	
Contents	
1 Introduction	11
2 Ground-penetrating radar	12
2.1 Propagation of electromagnetic waves in glacier ice	14
2.2 The electromagnetic wave propagation velocity in glacier ice	17
2.3 Surveying of the radar profiles	18
3 Svalbard-type polythermal glaciers	19
4 GPR applications in studying polythermal glaciers	22
5 Summary of original papers	24
6 Conclusions	27
References	
Original Papers	

1 Introduction

The main purpose of this Thesis is to emphasise how Ground Penetrating Radar (GPR) can be used in different glaciological studies: in mapping the inner structure, determining accumulation, estimating water contents, mapping drainage channels or observing hydrothermal properties such as superimposed ice. The Thesis also aims to improve current knowledge on Svalbard polythermal glaciers: their hydrothermal properties, drainage and behaviour in the changing climate.

Work on glacier recession lends considerable support to the rise in global temperatures since the late 19th century and casts further light on regional or world-wide temperature changes before the instrumental era (IPCC 2001). Glaciers are important locally in the hydrological cycle, energy balance and tourism. Globally they affect to surface temperature by being effective back-scatters of the incoming solar radiation. Sea-level changes are highly related to the variations in the extents of the glaciers.

About 60% of Svalbard (36 600 km²) is covered by glaciers of various types (Hagen et al., 1993). Although this is less than 1% of the total glaciated area of earth's land surface, globally it is an important area to study glacier behaviour because of the short response times of the glaciers to changes in climate compared to the ice-sheets of Antarctica and Greenland. Svalbard glaciers are classified as sub-polar or polythermal in respect of their thermal structure (Schytt 1969; Baranowski 1977), typically containing layers of ice that are both at and below the freezing point. This means that their structure is different and more complex than the well-studied mountain glaciers in temperate regions, and therefore their response to changes in climate is also different and more complex and needs careful studying.

The main focus in the Thesis is the hydrothermal structure of the polythermal glaciers in Svalbard. This is discussed in detail in papers II, III and IV. Paper II describes the firn-ice transition zone properties common to four Svalbard polythermal glaciers and paper III is a detailed study of the hydrothermal structure and water content of one Svalbard glacier. In paper IV, GPR data was used to model the drainage pattern of two polythermal glaciers. The Thesis also includes a study of spatial and temporal snow accumulation (paper I) and a study about glacier recession from southern Svalbard (paper V). Overall the Thesis contains a unique set of GPR data and unique information on the hydrothermal properties of several large Svalbard glaciers.

2 Ground-penetrating radar

A radar commonly used in glaciological studies is the so-called pulse radar. The transmitter antenna mounted on a moving platform (plastic sledge or pulka) emits an electromagnetic pulse to the media (snow and ice). The emitted electromagnetic wave penetrates the snow and ice and is reflected by the different dielectric surfaces in the media like annual snow and firn layers, inhomogenities in the ice, and finally the glacier bed. The reflected waves are collected by the receiver antenna on the moving platform. The antenna frequencies used normally vary from 50 MHz to 1 GHz. Frequency-modulated continuous wave radars (FM-CW radar) have become common especially in snow accumulation studies (e.g. Forster *et al.* 1991; Richardson-Näslund 2001). FM-CW radar transmits a sequence of electromagnetic waves at number of different frequencies distributed over an adjustable bandwidth (e.g. Hamran *et al.* 1995).

The received electromagnetic information from the media travels from the receiver antenna through cables to a control unit. The control unit measures the time difference between the transmitted and received pulse (travel-time) and it's amplitude. The propagation speed in the ice and the depth of the reflecting features is calculated from the travel time. The propagation speed is dependent on the dielectric properties of the media. Snow and ice have different dielectric properties but glacier ice is relatively homogenous. It is therefore often assumed that the propagation speed is constant through the ice, but in the case of polythermal glaciers this should be considered with caution because of the greater water content of the temperate ice compared to that of cold-ice. A snow pack can also have large variations in its dielectric properties since they are strongly density dependent (e.g. Evans 1965; Glen & Paren 1975). Therefore in radar studies of snow, the gradual increase in density with increasing depth must be considered in order to obtain accurate depth values (Richardson-Näslund 2001). The propagation speeds in different snow and ice layers can be measured by doing a common-depth-point measurement (see e.g. Pälli 1998 for the technique) and it is necessary to do for polythermal glaciers.

The final output of the ground-penetrating radar measurement is displayed on a computer screen as a continuous profile of different dielectric boundary surfaces and e.g. with the equipment used in this Thesis, it can be followed real time during the measurement. The collected data are processed in the office with commercially available data processing programs.

The radar used in this study was a commercially available pulse radar Ramac from Malå Geoscience. Antenna frequencies used were 25, 50 and 200 MHz. The 50 MHz and 25 MHz antennas were mounted on two plastic pulkas attached with ropes and pieces of wood parallel to each other. The antennas were separated by 2 m from each other and the whole system looked like a small catamaran pulled behind a snow scooter (Fig. 1). For the 200 MHz antennas a commercially available special pulka was used. The control unit and the computer were mounted on the snow scooter together with a GPS system to record radar position.

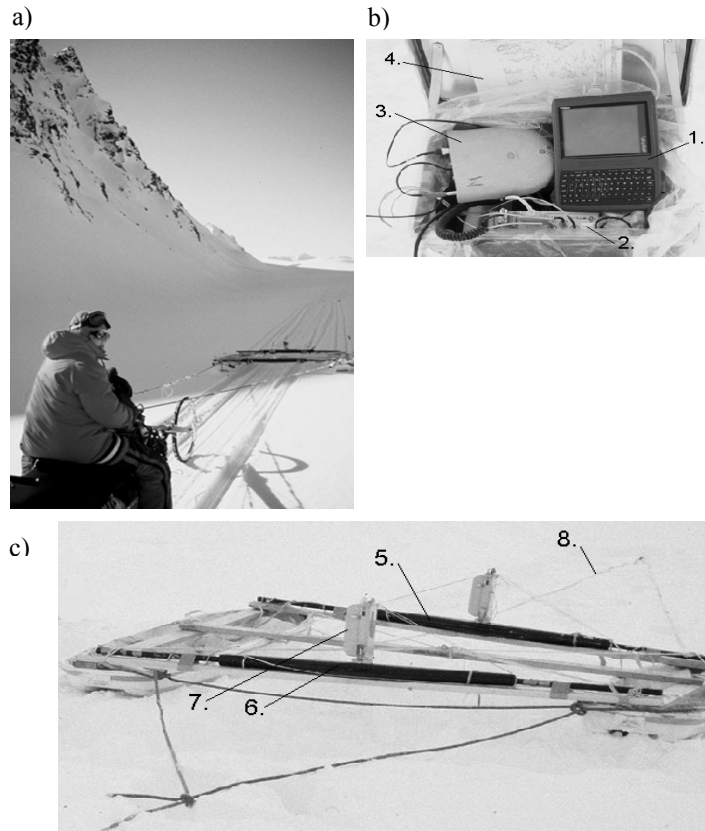


Fig. 1. a) A Ramac GPR with 50 Mhz antennas in operation. The measurement is done with two persons with one driving the snow scooter and other controlling the data collection. The positioning is done with GPS but an odometer wheel (in the Figure just behind the snow scooter) is also used. b) A closer look to a box placed on the back of the snow scooter. The computer (1), the control unit (2), the DGPS data collector (3.) and a map of the area (4.) are placed in the box. The measurement can be followed in-situ from the computer screen. c) The 50 MHz transmitter antenna (5.) and the 50 MHz receiver antenna (6.) are placed into two plastic pulkas tied together with a wooden frame and rope. The batteries (7.) are connected to each of the antenna and a long rope (8.) follows behind attached to an anchor preventing the pulkas from too much acceleration when going downhill.

2.1 Propagation of electromagnetic waves in glacier ice

Following Daniels (1996), electromagnetic wave propagation can be represented by a one-dimensional wave equation of the following form. Propagation is taken along the z -axis, with perpendicular electric and magnetic fields:

$$\frac{\partial^2 E}{\partial z^2} = \mu\epsilon \frac{\partial^2 E}{\partial t^2} \quad (1)$$

where E is the instantaneous electric-field component of an electromagnetic wave, μ is the absolute magnetic permeability of medium, $\mu = \mu_0\mu_r$ and ϵ is the absolute electric permittivity of the medium, $\epsilon = \epsilon_0\epsilon_r$. μ_r and ϵ_r are the relative permeability and permittivity of medium and μ_0 and ϵ_0 are the permeability and permittivity respectively of free space. t is the propagation time.

The velocity of propagation (m/s) :

$$v_r = \frac{1}{\sqrt{\mu\epsilon}} = \frac{c}{\sqrt{\epsilon_r}} \quad (2)$$

where c is the velocity of light in free space.

Electromagnetic waves propagating through natural media suffer losses to either the electric or magnetic fields, or both. This causes attenuation of the original electromagnetic wave. Absorption of electromagnetic waves is caused by both conduction and dielectric permittivity. For most materials like ice or snow, the magnetic response is weak and need not to be considered. The complex permittivity ϵ and the complex conductivity σ may be expressed as:

$$\epsilon = \epsilon' - j\epsilon'' \quad (3)$$

and

$$\sigma = \sigma' - j\sigma'' \quad (4)$$

where ϵ' and σ' are real parts, ϵ'' and σ'' are imaginary parts and $j = \sqrt{-1}$. The nature of parameter ϵ' relates to the electric permittivity, which may also be expressed in terms of relative permittivity. The parameter ϵ'' relates to losses associated with both conductivity and frequency.

On a conducting dielectric, the parameters measured are the apparent permittivity $\tilde{\epsilon}$ and apparent conductivity $\tilde{\sigma}$:

$$\tilde{\epsilon} = \epsilon'_e - j\epsilon''_e \quad (5)$$

$$\tilde{\sigma} = \sigma'_e - j\sigma''_e \quad (6)$$

The behaviour of a material may be specified either by its apparent permittivity or, equivalently, by its apparent conductivity since

$$\tilde{\sigma} = j\omega\tilde{\epsilon} \quad (7)$$

where ω is the angular frequency of an electromagnetic wave.

In terms of wave-propagation equations, ε and σ always occur in the combination

$$\sigma + j\omega\varepsilon \equiv \sigma'_e + j\omega\varepsilon'_e \quad (8)$$

where σ'_e and ε'_e are the real effective conductivity and permittivity

$$\sigma'_e = \sigma' + \omega\varepsilon'' \quad (9)$$

$$\varepsilon'_e = \varepsilon' - \frac{\sigma''}{\omega} \quad (10)$$

At a flat boundary between two semi-infinite media, some energy will be reflected and the remainder transmitted. The reflected field strength is described by the reflection coefficient r :

$$r = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad (11)$$

where η_1 and η_2 are impedances of media 1 and 2, respectively. The intrinsic impedance η of a medium is the relationship between the electric and magnetic field and is a complex quantity:

$$\eta = \left(\frac{\mu}{\varepsilon} \right)^{\frac{1}{2}} = \sqrt{\mu} \left(\varepsilon' \left(1 - j \frac{\varepsilon''}{\varepsilon'} \right) \right)^{-\frac{1}{2}} \text{ Ohms} \quad (12)$$

The effect on a pulse waveform is to change the phase of the reflected wavelet so that targets with different relative permittivities to the host material show different phase patterns of the reflected signal. However, the amplitude of the reflected signal is affected by the propagation dielectric of the host material, the geometric characteristics of the target and its dielectric parameters. To gain a better insight into reflection process, Paren and Robin (1975) considered reflections arising from changes due to changes in either permittivity or conductivity alone. In the case of a reflection caused by changing permittivity only, r is proportional to the relative change in ε' , while for that for a change in conductivity alone, r is proportional to the absolute change in σ'/ω . In ice, a change in conductivity or permittivity can be caused by a variation in density, impurities, temperature, crystal size and orientation, or from a layer of another material such as moraine. Conductivity is dependent on the ice temperature and the concentration of several types of impurity in ice (Moore *et al.* 1994). Cold-ice is relatively transparent to radar waves and in general any dielectric discontinuity is detected. In high polar ice sheets at depths deeper than a few hundred meters changes in conductivity are thought to cause internal reflections rather than permittivity changes (Paren & Robin 1975).

Following Petrenko and Whitworth (1999), an attenuated plane electromagnetic wave of amplitude E_0 and angular frequency ω travelling in the $+x$ direction with velocity v at the moment of time t is described as:

$$E(x, t) = E_0 \exp\left(-\frac{\alpha x}{2}\right) \exp\left[i\omega\left(t - \frac{x}{v}\right)\right] \quad (13)$$

This wave has the property that the intensity $I(x)$ decays as

$$I(x) = I_0 \exp(-\alpha x), \quad (14)$$

and α^{-1} is defined as the absorption coefficient, with units of m^{-1} . For frequencies well above the Debye dispersion τ_D i.e. frequencies greater than 1 MHz the attenuation distance α^{-1} for electromagnetic waves in ice is independent of frequency up to the onset of the infrared absorption band at about 10 GHz. This window in the radio/microwave region makes it possible to use this waveband for ground penetrating radar sounding of glaciers and ice sheets (Fig. 2).

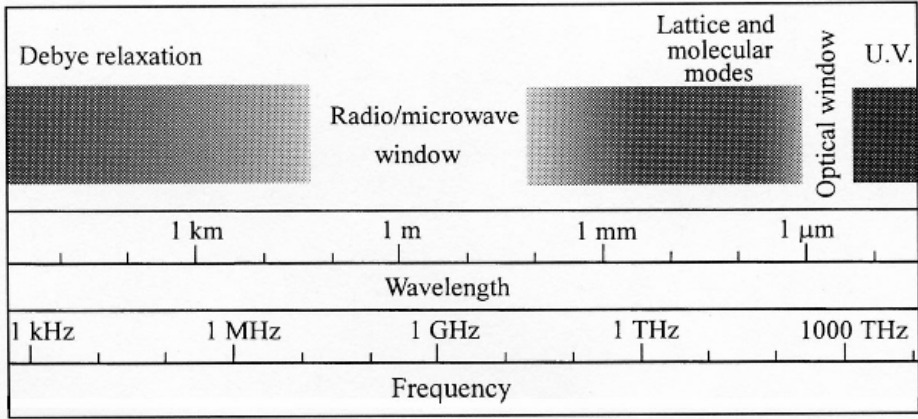


Fig. 2. Chart of the electromagnetic spectrum showing the Radio-microwave window suitable for GPR sounding of glaciers. (A modified reprint from Fig.9.1 of Petrenko & Whitworth 1999).

The penetration distance α^{-1} depends on the high-frequency conductivity σ_∞ according to equation:

$$\alpha^{-1} = \frac{\tau_D c \varepsilon_\infty^{1/2}}{\chi_s} = \frac{c \varepsilon_0 \varepsilon_\infty^{1/2}}{\sigma_\infty} \quad (15)$$

where χ_s is the electric susceptibility, and ε_∞ high-frequency permittivity. The transmission of the waves through ice is then independent of frequency, but dependent on temperature and impurity concentration through the conductivity σ_∞ . In pure polythermal glacier ice at the melting point $\sigma_\infty = 10^{-5} \text{ Sm}^{-1}$ and the attenuation becomes $\alpha^{-1} = 4.73 \text{ dB}/100 \text{ m}$. The water in the temperate ice layer is an effective backscatter and also attenuates the transmitted wave so usually the deepest reflections, such as that from the bedrock, can be difficult to distinguish because of the clutter from surrounding wet ice. Processing of the data can reduce this problem. The processing procedures used in each survey are mentioned in each paper I-V.

2.2 The electromagnetic wave propagation velocity in glacier ice

The propagation velocity of a GPR signal through an electrically resistive medium, such as a glacier, is dominantly a function of the bulk dielectric constant, ε_r , of the material (equation 2).

In polar snow and firn (i.e. composed of ice and air with no liquid water content) the dielectric permittivity ε_d for dry snow matrix near the melting point depends on the density of the firn (Frolov & Macheret 1999):

$$\varepsilon_d = (1 + 0.857 \rho_f)^2 \quad (16)$$

where ρ_f is the bulk density of the firn. For these conditions the two equations can be merged and the velocity can be expressed as:

$$v = \frac{c}{1 + 0.857 \rho_f} \quad (17)$$

The dielectric constant depends also of the water content W of the medium. The Looyenga formula is a particular case of an exponential model describing the dielectric permittivity, ε'_m of a mixture as a function of dielectric permittivities, ε'_k of k^{th} components with a volume portion f_k (Sihvola *et al.* 1985)

$$\varepsilon'_m{}^a = \sum f_k \varepsilon'_k{}^a \quad (18)$$

where $a = 1/3$. For a two-component dielectric mixture of ice and water, in which all the cavities are water filled the Looyenga formula is (Macheret & Glazovsky 2000):

$$\varepsilon_s = \left[\left(\varepsilon_i^{1/3} + W \left(\varepsilon_w^{1/3} - \varepsilon_i^{1/3} \right) \right) \right]^3 \quad (19)$$

where ε_s , ε_i and ε_w are dielectric permittivities of wet glacier ice, solid ice and water, respectively, and W is the water content fraction. If the glacier is a three-component mixture of ice with water and air inclusions, the Looyenga mixing formula gives the dielectric permittivity ε_s as (Macheret & Glazovsky 2000):

$$\varepsilon_s = \left[\varepsilon_i^{1/3} (1 - P) + W \varepsilon_w^{1/3} + P - W \right]^3 \quad (20)$$

where P is the total fractional water and air content, or total ‘‘porosity’’ of temperate ice. In the case of a cold glacier ice (a two-component dielectric mixture of ice and air) the permittivity ε_d according the Looyenga mixing formula is (Macheret & Glazovsky 2000):

$$\varepsilon_d = \left[\left(\frac{\rho_d}{\rho_i} \right)^{1/3} \left(\varepsilon_i^{1/3} - 1 \right) + 1 \right]^3 \quad (21)$$

where ρ_d is the density of cold glacier ice (a two-component mixture of ice and air) and ρ_i the density of solid ice ($\rho_i = 0,917 \text{ Mgm}^{-3}$).

2.3 Surveying of the radar profiles

The first positioning system used was a hand-held Garmin Global Positioning system (GPS) but since 1999 a Javad differential GPS (JPS) has been used. The positioning accuracy with differential GPS in kinematic mode is of order centimetres and in static mode of order millimetres. The final accuracy of the measured profiles decreases slightly when the positioning data is tied together with the radar data. Usually GPS data are collected every 5 s concurrently with the GPR data. The GPS data is stored to the JPS receiver and downloaded afterwards to a computer. The positioning of the radar profiles was done with the radar data processing program Haescan (Roadscanners Oy). Haescan can not read the JPS file and so can not do the positioning automatically. Some measured co-ordinates from the JPS file must be given manually to the program as well as the corresponding scan number and the place (in meters) along the profile. Haescan can then count the rest of the scans and calculate co-ordinates by linear interpolation. The final positioning files usually need editing because of gaps in either the data sets. Gaps in the GPR data are usually from attempting to collect data at too high a rate, i.e. the control unit buffer becomes full or because of problems in the antenna or the cable connections. Gaps in the GPS data are usually because of driving too close to mountains or other reasons leading to too few satellites being observable such as when clouds are low and visibility is also poor due to large amounts of snow or water vapour in the air, as is experienced often on Svalbard. All gaps in both the data sets need to be found manually and possible adjusting done before the datasets are tied together with Haescan or while editing the positioning file. This is usually a very time-consuming job, because the measured profiles are 5-20 km long, so the positioning files are huge. The best solution for the problem would be that Haescan could read the JPS-files directly, or a develop radar interpretation program in Matlab or similar software.

More detailed the GPS technique used in each GPR survey is introduced in the papers I-V.

3 Svalbard-type polythermal glaciers

Most of the glaciers in Svalbard (Fig. 3) have been classified as polythermal. This means that they have a layer of cold-ice (temperature below melting point) on top of the temperate ice layer (temperature at the melting point) in their ablation zones (Fig.4). Polythermal glaciers are widely spread, not only on Svalbard, but also in other regions of the world: the Alps (Blindow & Thyssen 1986), Canadian Arctic (Blatter 1987), the Caucasus (Macheret & Luchininov 1973), Polar Urals (Macheret & Luchininov 1971) and Altai (Nikitin & Osipov 1989). Svalbard-type polythermal glaciers are different from Canadian high Arctic polythermal glaciers, which consist predominantly of cold-ice with a thin layer of warm basal ice beneath the centre of the ablation area (Blatter 1987; Blatter & Kappenberger 1988).

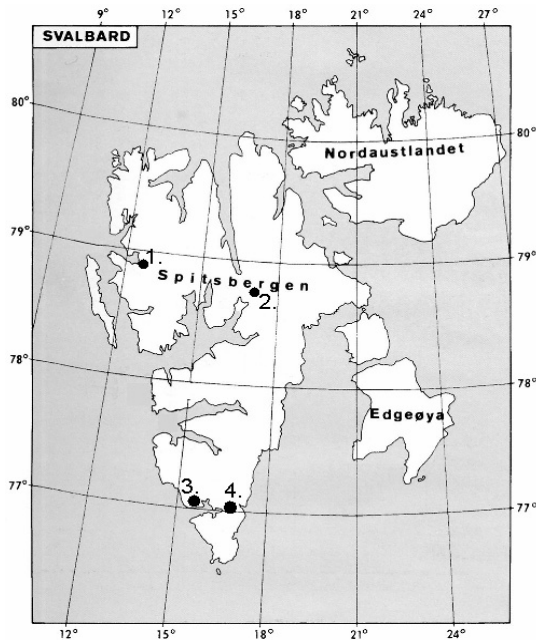


Fig. 3. Map of Svalbard (modified from Fig. 2.15 of Jania & Hagen 1996). The glaciers where the data were collected with GPR for this Thesis are numbered 1) Kongsvegen, 2) Lomonosovfonna, 3) Hornsund, 4) Hornbreen-Hambergbreen

The firn line (i.e. snow line) marks the transition zone where to down-glacier cold-ice layer is on top of the temperate ice layer at the surface. The transition from water-permeable firn to impermeable cold-ice evolves as the snowpack in the upper firn part of the glacier becomes wet with meltwater in the summer (e.g. Müller 1962). The water that percolates down and partly refreezes in the deeper layers raises the temperature of the firn to the melting point. However, down-glacier of the firn line the ice becomes impermeable because of cold ice, preventing penetration of meltwater except via crevasses or moulins. The surface ice is then cooled below the melting point during winter. The complex firn-ice transition is important to study carefully as the contribution from superimposed ice to glacier mass balance is very significant on Svalbard glaciers. The equilibrium line, which is not a physically marked feature on polythermal glaciers, is somewhere in the superimposed ice zone. The firn transition zone properties of four different Svalbard polythermal glaciers: Hansbreen, Werenskioldbreen, Kongsvegen and Nordenskiöldbreen are discussed in paper II and III.

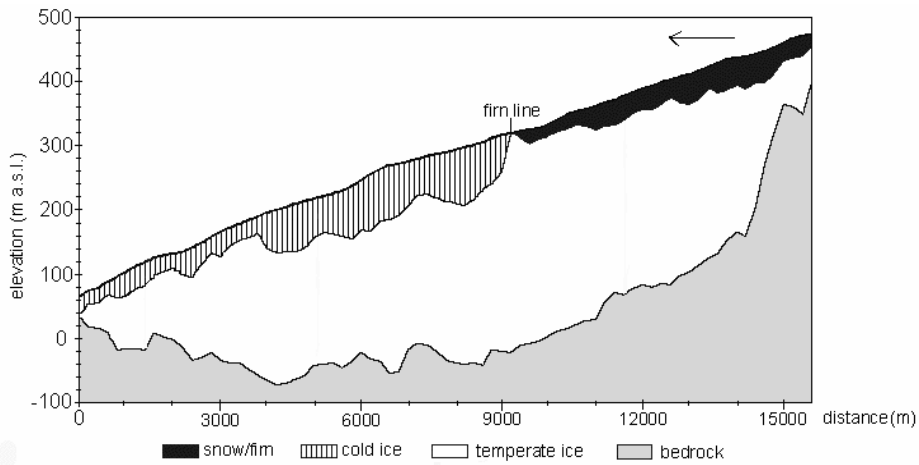


Fig. 4. A typical Svalbard-type polythermal glacier structure, showing the cold-ice layer on top of temperate ice. This example is the longitudinal profile of Hansbreen. The thickness of the glacier and the bedrock structure are highly variable between different glaciers. The firn line marks the position of the occurrence of cold-ice at the glacier surface. The glacier flow direction is marked with a black arrow.

Most glaciers studied in the Thesis are also tidewater and surging glaciers. A tidewater glacier front is grounded in a fjord with water level subject to tidal influence. It loses mass by huge calving processes. The calving rate (the volume of icebergs discharged per unit time per unit vertical area of the terminus) is proportional to the water depth at the terminus (Paterson 1994). 36% of the Svalbard glaciers may be of surge-type (Hamilton & Dowdeswell 1996). During a surge, a large volume of ice is transferred from a reservoir area to the terminal part of the glacier (Paterson 1994).

Because of the tidewater, surge and polythermal nature of many Svalbard glaciers the mass balance calculations are more complicated than of e.g. Alpine mountain glaciers. Hydrothermal structure and mass balance of polythermal glaciers depend on spatial distribution of ice formation zones including superimposed ice and equilibrium line altitude (Ødegard *et al.* 1997; Macheret & Glazovsky 2000). Therefore detailed information from the hydrothermal and dynamical properties of these glaciers is essential. The hydrothermal regime and dynamics of polythermal glaciers are sensitive to glacioglimatic conditions (Macheret & Glazovsky 2000) and their spatial and temporal change can be considered an indicator of short-term and long-term climate change (Macheret *et al.* 1992; Glazovsky *et al.* 2003).

The glacier response to climate changes is not only measured by mass-balance calculations but by changes in their front position and dynamics. A tidewater or a surge-type glacier front position is not directly related to the changes in climate and therefore their front position can not be used solely as an indicative of the glacier response to climate changes.

4 GPR applications in studying polythermal glaciers

An early use of radar to probe into glaciers was in early 1950s, when radar techniques were concluded to be a viable method of measuring ice thickness (Steenso 1951). An airborne system to carry out radar sounding from helicopters and fixed wing aircrafts was proposed by Cook (1960). Radio-echo sounding (RES) technique was first used in Antarctic studies in the early 1960s to measure ice thickness (e.g. Waite & Schmidt 1962; Evans 1963). The airborne technique was first only used on cold-ice-sheets of Antarctica and Greenland but since 1966 the radio-echo sounding method has been used to investigate mountain glaciers also (Macheret & Zhuravlev 1982). In 1967 the potential of using RES method on temperate mountain glaciers was confirmed by investigations in the Caucasus at a frequency of 440 MHz (Macheret & Sukhanov 1970). The investigations showed that interpretation of the data obtained was complicated because of a great amount of clutter, and indicated the necessity of applying special methods and equipment different from those used on cold-ice sheets. In 1972-74 good results from tests of special equipment designed for RES of temperate glaciers were obtained (Goodman 1973; Watts *et al.* 1975) and later similar modified equipment was also successfully applied on other glaciers in Canada, USA and Iceland (Goodman 1975; Goodman *et al.* 1975; Clarke & Goodman 1975; Björnsson *et al.* 1977; Miller 1979).

The first land-based radio-echo sounding in Svalbard was performed on a glacier located in the Adventfjorden region (Liestøl 1974). In 1974-75 and 1977-79 radio-echo sounding of Svalbard glaciers was carried out from helicopters and terrestrial vehicles by a Soviet expedition (Macheret & Zhuravlev 1982, 1985). Airborne measurements from helicopters were performed on 87 glaciers of various types, using 440 MHz aircraft radio-altimeter and 620 MHz special equipment. Ground-based radar sounding were also carried out on some of the glaciers including detailed surveys of ice thickness and sub-ice relief and also certain radiophysical measurements (Macheret & Zhuravlev 1982). The Soviet group obtained bed reflections with an ice thickness of 540 m, as well as reflections from internal reflection boundaries on some glaciers. In 1980 a British-Norwegian group studied 45 Spitsbergen glaciers by airborne radio-echo sounding using 60 MHz S.P.R.I. Mk IV equipment designed originally for deep cold-ice in Antarctica and Greenland (Dowdeswell *et al.* 1984). The majority of the glaciers in Svalbard were flown

over by these two groups and the general scheme of polythermal glacier structure was confirmed.

Impulse radar system improved ground-penetrating radar technique greatly and made it usable also on temperate ice. From the early 1990s until today ground-based radar soundings have provided a more detailed and complex picture of the thermal structure of many Svalbard glaciers. Macheret and others (1993) studied two "two-layered" Svalbard glaciers Fridtjovbreen and Hansbreen using a low-frequency (2-13 MHz) GPR and identified their internal and bed reflection horizons. They also calculated estimates of the water content and characterised the hydrothermal state of these two glaciers from their individual parts. Björnsson and others (1996) studied in 1990 the thermal regimes of four polythermal glaciers in Kongsfjorden and Hamran and others (1996) estimated the water content of Uvérsbreen from the GPR backscattered energy. Ødegård and others (1997) used a time-gated synthetic pulse radar at 10 MHz-1 GHz and temperature measurements from boreholes to study the thermal structure of Finsterwalderbreen.

The potential of a commercial high-resolution GPR for mapping internal glacial structure of high-Arctic glaciers was finally clearly demonstrated in studies of Murray and others (1997) on Bakaninbreen. Since the late 1990s the use of commercial GPR has become more and more popular among glaciologists working in Svalbard. Most GPR studies of Svalbard polythermal glaciers have concerned the bedrock mapping and mapping the internal thermal structure like the boundary between cold and temperate ice. However there have been other applications such as Macheret and Glazovsky (2000) who have studied several Svalbard glaciers with GPR and used the results for estimation of the water content of the studied glaciers. The snow accumulation distribution on Spitsbergen has been studied with GPR by Winther and others (1998).

This study is unique in using collected GPR data for estimating temporal snow accumulation variation in Svalbard (paper I), mapping superimposed ice with ground-based radar and establishing common firn-ice transition zone features for several Svalbard polythermal glaciers (paper II), determining a tidewater polythermal glacier hydrological behaviour and drainage patterns (paper IV), as well as monitoring past change and possible future of the southern Svalbard glaciers (paper V).

5 Summary of original papers

Paper I

Pälli A, Kohler J, Isaksson E, Moore J, Pinglot F, Pohjola V & Samuelsson H (2002) Spatial and temporal variability of snow accumulation using ground-penetrating radar and ice cores on a Svalbard glacier. *Journal of Glaciology* 48, 162: 417-424.

In this study ground-penetrating radar data and data from one deep and two shallow ice-cores were successfully used to determine spatial and temporal variation of snow accumulation on a longitudinal profile of a polythermal glacier Nordenskjöldbreen, Svalbard. This was the first study of long-term (on a scale of several tens of years) accumulation rates and their spatial and temporal variation in Svalbard using GPR. Two internal radar reflection horizons were dated using parameters measured in the deep core. The horizons were followed from the deep core along the profile. The radar travel-times were converted to water equivalent, yielding accumulation rates along the profile for three time periods: 1986-99, 1963-99 and 1963-86. A spatial variation of 40-60% in snow accumulation over short distances along the profile were observed. The results indicated increased accumulation in the late 1980s and 1990s since the annual accumulation rate for 1986-99 was found to be 12% higher than for the period 1963-86. The paper illustrates the importance of combining GPR and ice-core data, as the accumulation rate measured from the deep core at the summit of Lomonosovfonna showed no increase in precipitation. Though the observed increase is within the estimated error limits of the radar survey, it is consistent with recent changes in precipitation in Svalbard.

Paper II

Pälli A, Moore J.C & Rolstad C (2003) Firn-ice zone features of four polythermal glaciers in Svalbard seen by ground-penetrating radar. In press to *Annals of Glaciology* 37.

This paper compares and discusses hydrothermal properties determined from detailed ground-penetrating surveys of four different Svalbard polythermal glacier: Hansbreen, Werenskiöldbreen, Nordenskjöldbreen and Kongsvegen. The firn line and the whole firn-ice transition zone was clearly detected with GPR using 200 and 50 MHz antenna frequencies. A different slope of the cold/temperate ice boundary at the firn line was found for each of the four polythermal glaciers. On each of the glaciers, the radar profiles

show continuous layers typically about 2 m apart from each other up-glacier from the firn line. They are observed in the top 10-20 m of firn and increase in thickness up-glacier. These layers were interpreted as likely to be from layers of ice lenses and relatively low-density firn in the firn area, and from bubble-rich and bubble-poor ice in the superimposed ice zone. At the firn line reflections from the cold-ice layer disappear and the whole thickness of ice becomes temperate. Similar structures like foliations and superimposed ice in the firn-ice transition area were observed, though with different emphasis on each glacier. The limited resolution and the sporadic nature of the reflections means that the overall extent of superimposed ice is difficult to measure accurately, though there is encouraging similarity between GPR and satellite imagery for superimposed ice. The nature of the reflections in the superimposed ice is uncertain, but most easily explained by increased water content of a few percent at sporadic locations within the superimposed ice. The dipping foliations in the glacier ice down-glacier of the firn line show that the layered reflections from the firn line are preserved, though in much weaker form, even when the firn has been transformed to solid ice.

Paper III

Moore J.C, Pälli A, Ludwig F, Blatter H, Jania J, Gadek B, Glowacki P, Mochnacki D & Isaksson E (1999) High-resolution hydrothermal structure of Hansbreen, Spitsbergen, mapped by ground-penetrating radar. *Journal of Glaciology* 45, 151: 524-532.

In this study we have mapped at high lateral and vertical resolution the hydrothermal structure of Hansbreen with GPR. The GPR data shows that the hydrothermal structure of the glacier is highly variable both along the centre line and on transverse profiles. The cold-ice-temperate ice boundary coincides with the water table data from moulins and the melting point found from borehole thermometry. In general the temperate ice contains 1-2% water, but water contents of about 4% are associated with places which might be buried water channels or water-filled near surface crevasses or moulins. The evidence that wet ice sometimes overlays drier ice shows the hydrothermal structure to be very complex.

Paper IV

Pälli A, Moore J.C, Jania J, Kolondra L & Glowacki P (In press to *Polar Research*) The drainage pattern of two polythermal glaciers: Hansbreen and Werenskioldbreen in Svalbard.

This study improves the understanding of a Svalbard-type polythermal glacier drainage. Hydraulic geometry models of the subglacial hydrology of two contrasting glaciers Hansbreen (a calving glacier) and Werenskioldbreen (terminating on land) in Svalbard have been constructed. Validation of the models was done using field-observations including location mapping and speleological exploration of active moulins, positions of main river outflows, dye-tracing and water chemistry experiments, and observations of water pressure inside moulins. The results suggest that the water pressure is generally rather high, but varies greatly depending on local conditions such as glacier bed morphology, the thickness of cold-ice layer, the thickness of the glacier and seasonal changes in meltwater input. It seems that on Hansbreen water pressure remains high all winter because the subglacial drainage system is not developed and the water is not able to escape from the cavities. In summer Hansbreen has a well developed drainage system,

that can rapidly adjust to large water volumes. Werenskioldbreen drainage system seems to be well channelized during the melting period and the models suggest a dendritic drainage system. The high mineralization of the outflow water and the cold basal front of the glacier suggest that the water might flow in subterranean channels close to the terminus. Water reservoirs also exist in winter since a vast naled ice field is formed in front of Werenskioldbreen. Therefore water pressure might be at ice-overburden close to the Werenskioldbreen front all winter. We conclude that geometric quantities derived from DEMs (hydraulic potential and upstream area maps) can be used as mesoscale hydrological predictors. The models give an insight into the basin-scale drainage structure of the glaciers, although they are unable to predict exactly the outflow positions and the positions of the smaller drainage axes. The modelling of polythermal glacier drainage may be improved with a better understanding of the role of their specific thermal regime, which seems most likely to be achieved by more field data on water level in ice and its seasonal variations.

Paper V

Pälli A, Moore J.C, Jania J & Glowacki P (2003) Glacier changes in southern Svalbard 1901-2000. In press to *Annals of Glaciology* 37.

In this study we have compared GPR and GPS data from the year 2000 to glacier surface height and glacier front length data from 1936 and 1901. Hornbreen and Hambergbreen and several surrounding glaciers in southern Svalbard were mapped with ground-penetrating radar together with DGPS (Differential global positioning system). Digital elevation models (DEM) were constructed of the bedrock and surface data sets. The surface DEMs and the DGPS data from some individual points were compared with data from topographic mappings from 1936 oblique stereoscopic aerial photos and from Mission Russe, a Russian-Swedish expedition in 1899-1901. The bedrock data was used to calculate the thickness of the glaciers and to determine if there exists a continuous sub-sea-level channel between Torell Land and Sørkapp Land. No continuous sub-sea level path was found, though the bed of Hornbreen and Hambergbreen lies at -25-25 m a.s.l. This result resolves a problem discussed in earlier publications (e.g. Macheret & Zhuravlev 1985). The results show significant change in area and volume of all the surveyed glaciers. Hornbreen and Hambergbreen are 60-100 m thinner today in their upper parts than at the beginning of the century and their volume has decreased by 37-50%. Hornbreen has retreated by 13.5 km from the front and Hambergbreen by 16 km. Also the fronts of the surrounding east coast glaciers have retreated. Hornbreen and Hambergbreen surface profiles have become steeper and they have sub-sea level fronts. We conclude that the most likely future scenario is that the low-lying glaciated valley filled by Hornbreen and Hambergbreen will become a partially inundated ice-free isthmus within the relatively near future.

6 Conclusions

1. Ground-penetrating radar soundings of polythermal glaciers, assessed with ice core studies, borehole-thermometry or moulin water-level measurements compose a powerful tool in glaciological studies. It is possible to resolve the spatial and temporal variations of snow accumulation, determine the drainage pattern, hydrothermal structure and firn-ice transition properties in great detail. Differential GPS survey combined with GPR sounding can supply important information of the current state of Svalbard polythermal glaciers.
2. The bedrock mapping with GPR has revealed important results. According to GPR data Hansbreen has a reverse sloped bed, starting ca. 4 km from the terminus. The reverse sloped bed has a great effect on glacier hydrological pattern and dynamics. Most of the studied glaciers have sub sea-level fronts. Bedrock data shows thresholds and pits that also affect on the drainage pattern and therefore the dynamics. Foliations have been shown to follow the bedrock pattern.
3. GPR and ice cores in combination can be used to estimate temporal changes in accumulation more accurately than at the core site, whose values may be dependent on specific local conditions. Large spatial variation of 40-60% in snow accumulation over short distances are mostly explained because of the local topography but some of variability is due to wet firn, causing too long travel times and too deep inferred layer depths. Snow accumulation has increased over the past decade on Lomonosovfonna, Svalbard. The result is within the conservative error limits but consistent with meteorological records at Hornsund, Longyearbyen and Ny-Ålesund.
4. The firn-line can be easily detected and the firn-ice transition mapped in detail with GPR using both 50 and 200 MHz antennas. Characteristic patterns of reflection were compared with satellite images and are shown to be caused by superimposed ice, but the overall extent of superimposed ice can not be estimated with GPR due to the limited resolution and the sporadic nature of the reflections. Features such as reflecting horizons likely from layers of ice lenses and relatively low-density firn, foliations, bigger water channels, moulins and crevasses were observed in all four surveyed glaciers though with different emphasis on each glacier.

5. GPR studies of polythermal glaciers show that the hydrothermal structure of each glacier studied is highly variable both along the centre-line and on transverse profiles. The cold-ice thickness varies in general between 20 – 120 m. On Hansbreen the cold-ice layer is at maximum 100 m thick just below the firn line, generally thinning down-glacier towards the terminus. Water contents of a glacier can be calculated by estimating radar wave-velocities to point reflectors. On Hansbreen the typical water content of temperate ice is 1-2%. Higher water contents of ca. 4% are associated with surface crevassing and moulins. The hydrothermal structure is shown to very complex, because there is evidence that wet ice sometimes overlays drier ice. Temperature gradients in the cold-ice indicate freezing rates of temperate ice below the cold-ice of $0.1-0.5 \text{ m a}^{-1}$. Isolated point reflectors within the cold-ice indicate large water-filled bodies that may survive for many years considering the temperature gradient in cold-ice.
6. The drainage pattern of a polythermal glacier can be derived from digital elevation models based on GPR and GPS data and the result can be used as a hydrological prognosis. The water pressure in polythermal glacier is generally rather high, close to ice over-burden pressure, but varies greatly depending on local conditions such as bed location, the thickness of cold-ice layer, the thickness of the glacier and seasonal changes in meltwater input.
7. There has been a very significant change in area and volume of southern Svalbard glaciers, Hornbreen, Hambergbreen and their adjacent glaciers, during the past 100 years. Hornbreen and Hambergbreen are situated below their equilibrium lines, they are thin and their beds in their frontal parts are below sea level. Hornbreen has become steeper since 1936. It seems that the two glaciers are unable to build-up the reservoir-area mass and geometry for a new surge. Therefore the low-lying glaciated valley filled with Hornbreen and Hambergbreen may become a partially inundated ice-free isthmus within the relatively near future (perhaps 100 years). Sørkapp Land would not become an island if the ice of the two glaciers is removed, since there is no continuous sub sea-level channel between Torell Land and Sørkapp Land.

References

- Baranowski S (1977) The sub-polar glaciers of Spitsbergen seen against the climate of this region. *Acta Univ. Wratislava*, 410.
- Björnsson H, Ferrari RL, Miller KJ & Owen G (1977) A 1976 radio echo sounding expedition to the Vatnajökull ice cap, Iceland. *Polar Record* 18, 115: 375-377.
- Björnsson H, Gjessing Y, Hamran S-E, Hagen J-O, Liestøl O, Pálsson F & Erlingsson B (1996) The thermal regime of sub-polar glaciers mapped by multi-frequency radio-echo sounding. *Journal of Glaciology* 42, 140: 23-32.
- Blatter H (1987) On the thermal regime of an arctic valley glacier: a study of White Glacier, Axel Heiberg Island, N.W.T., Canada. *Journal of Glaciology* 33, 114: 200-211.
- Blatter H & Kappenberger G (1988) Mass balance and thermal regime of Laika Ice Cap, Coburg Island, N.W.T., Canada. *Journal of Glaciology*, 34 116: 102-110.
- Blindow N & Thyssen F (1986) Ice thickness and inner structure of the Vernagtferner (Ötztal Alps): results of electromagnetic reflection measurements. *Zeitschrift für Gletscherkunde und Glazialgeologie* 2, 1:43-60.
- Clarke GKC & Goodman RH (1975) Radio echo soundings and ice-temperature measurements in a surge-type glacier. *Journal of Glaciology* 14, 70: 71-78.
- Cook JC (1960) Proposed monocycle-pulse very-high-frequency radar for airborne ice and snow measurements. *AIEE Common Electronics* 51: 588-594.
- Daniels DJ (1996) Surface penetrating radar. The Institute of Electrical Engineers, London, UK, 300.
- Dowdeswell JA, Drewry DJ, Liestøl O & Orheim O (1984) Radio-echo sounding of Spitsbergen glaciers: problems in the interpretation of layer and bottom returns. *Journal of Glaciology* 30, 104: 16-21.
- Evans S (1963) Radio techniques for the measurement of ice thickness. *Polar Record*, 11, 73; 406-410.
- Evans S (1965) Dielectric properties of ice and snow-review. *Journal of Glaciology* 5, 42:773-792.
- Forster RR, Davis CH, Rand TW & Moore RK (1991) Snow-stratification investigation on an Antarctic ice stream with an X-band radar system. *Journal of Glaciology* 37, 127: 323-325.
- Frolov AD & Macheret Yu Ya (1999) On the dielectric properties of dry and wet snow. *Hydrological Processes* 13: 1755-1760.
- Glazovsky AF, Krass MS, Krynsky AV, Macheret Yu Ya & Merzlikin VG (2003) Modelirovaniye gidrotermicheskogo rezhima i dinamiki subpolyarnykh lednikov. [Modelling of regime and dynamics of subpolar glaciers]. *Materialy Glataiologicheskikh Issledovaniy* [Data of Glaciological studies] 94:3-16.
- Glenn IW & Paren IG (1975) The electrical properties of snow and ice. *Journal of Glaciology* 15, 73:15-37.

- Goodman RH (1973) Time-dependent intraglacier structures. *Journal of Glaciology* 12, 66: 512-513.
- Goodman RH (1975) Radio echo sounding on temperate glaciers. *Journal of Glaciology* 14, 70: 57-69.
- Goodman RH, Clarke GKC, Jarvis GT, Collins SG & Metcalfe R (1975) Radio soundings on Trapridge Glacier, Yukon Territory, Canada. *Journal of Glaciology* 14, 70: 79-84.
- Hagen J-O, Liestøl O, Roland E & Jørgensen T (1993) *Glacier Atlas of Svalbard and Jan Mayen*. Norsk Polar Institutt Meddelelser 129. Oslo.
- Hamilton GS & Dowdeswell A (1996) Controls on glacier surging in Svalbard. *Journal of Glaciology* 42, 140: 157-168.
- Hamran S-E, Aarholt E, Gjessing DT & Hjeltnad J (1995) Ground-penetrating synthetic pulse radar; dynamic range and modes of operation. *Journal of Applied Geophysics* 33: 7-14.
- Hamran S-E, Aarholt E, Hagen J-O & Mo P (1996) Estimation of relative water content in a sub-polar glacier using surface-penetration radar. *Journal of Glaciology* 42, 142: 533-537.
- I.P.C.C. (2001) *Climate Change: Impacts, Adaptation and Vulnerability*. The IPCC Third Assessment Report, Cambridge University Press, Cambridge and New York.
- Jania J & Hagen J-O (eds.) (1996) *Mass Balance of Arctic Glaciers*. IASC report No. 5. University of Silesia, Poland.
- Liestøl O (1974) Glaciological work in 1972. *Norsk Polarinstitutt Årbok, 1972*: 125-135
- Macheret Yu Ya & Sukhanov LA (1970). Opyt primeneniya impul'snogo vysotomera RV-10 dlya izmereniya tolshchiny "teplykh" gornyykh lednikov s ikh poverkhnosti [Experience in the application of a RV-10 impulse altimeter for measuring the thickness of temperate mountain-type glaciers from their surface]. *Materialy Glyatsiologicheskikh Issledovaniy*. *Khronika*. *Obsuzhdeniya* 17: 60-72.
- Macheret Yu Ya & Luchininov VS (1971) Electromagnitnoye zondirovaniye tyeplykh gornyykh lednikov. [Electromagnetic sounding of temperate mountain glaciers]. *Zhurnal technicheskoy Fiziki* [Journal of Technical Physics] 41, 6:1200-1309.
- Macheret Yu Ya. & Luchininov VS (1973) Interpretatsiya resul'tatov lontanoy radiolokatsionnoy syemki tyeplykh gornyykh lednikov. [Interpretation of results of ground-based radar survey of temperate mountain glaciers]. *Materialy Glaciologicheskikh Issledovaniy* [Data of Glaciological studies] 22:45-57.
- Macheret Yu Ya & Zhuravlev AB (1982) Radio-echo sounding of Svalbard glaciers. *Journal of Glaciology* 28, 99: 295-314.
- Macheret Yu Ya & Zhuravlev AB (1985) Tolstchina ob'yem I stroyeniye lednikov (Thickness, volume and structure of glaciers). In: Kotlyakov, V.M. (ed.) *Glyatsiologiya Shpitsbergena* (Glaciology of Spitsbergen). Moscow, Nauka, 7-35 (Rezul'taty Issledovaniy po Mezhdunarodnym Geofizichaskim Proyektam. Unnumbered Series.)
- Macheret Yu Ya, Glazovsky AF, Krass MS, Bozhinsky AN, Ignatieva IYu, Konstatinova TN, Larina TB & Moskalevsky MYu (1992) Stroyeniye, gidrotermicheskoye sostoyaniye I rezhim subpolyasnykh lednikov. [Structure, hydrothermal state and regime of subpolar glaciers.] In V.M Kotlyakov (ed.) *Rezhim I dinamika polyarnyykh lednikovyykh pokrovov*. [Regime and dynamics of polar ice sheets.] Pp.48-115. St. Petersburg: Gidrometeoizdat.
- Macheret Yu Ya, Moskalevsky MYu & Vasilenko EV (1993) Velocity of radio waves in glaciers as an indicator of their hydrothermal state, structure and regime. *Journal of Glaciology* 39 132;373-384.
- Macheret Yu Ya & Glazovsky AF (2000) Estimation of absolute water content in Spitsbergen glaciers from radar sounding data. *Polar Research* 19, 2: 205-216.
- Miller KJ (1979) Under-ice volcanoes. *Geographical Journal* 145, 1: 36-55.
- Moore JC, Wolff EW, Clausen HB, Hammer CU, Legrand MR & Fuhrer K (1994) Electrical response of the Summit-Greenland ice core to ammonium formate, sulphuric acid and hydrochloric acid. *Geophysical Research Letters* 21: 565-568.
- Murray T, Gooch DL & Stuart GW (1997) Structures within the surge front at Bakaninbreen, Svalbard, using ground-penetrating radar. *Annals of Glaciology* 24; 122-129.
- Müller F (1962) Zonation in the accumulation area of the glaciers of Axel Heiberg Island, N.W.T., Canada. *Journal of Glaciology* 4, 33: 302 – 311.

- Nikitin & Osipov (1989) Tolschshina gorknykh lednikov: raschyetnye metody operdleniya, voznikayushchie oshibki i metody ikh umen'sheniya. [Ice thickness of mountain glaciers: calculated methods, arising errors and ways for their decreasing]. *Materialy Glacisologicheskikh Issledovaniy* [Data of Glaciological studies] 66:105-108.
- Ødegård RS, Hagen J-O & Hamran SE (1997) Comparison of radio-echo sounding (30-1000 MHz) and high-resolution borehole-temperature measurements at Finsterwalderbreen, southern Spitsbergen, Svalbard. *Annals of Glaciology* 24, 262-267.
- Parren JG & Robin G De Q (1975) Internal reflections in polar ice sheets. *Journal of Glaciology* 14, 71: 251-259.
- Paterson WSB (1994) *The Physics of Glaciers*. Third Edition, Oxford, etc., Elsevier.
- Petrenko VF & Whitworth RW (1999) *Physics of ice*. Oxford University Press, 373.
- Pälli A (1998) Analysis and interpretation of ground-penetrating radar data of polythermal glacier, Hansbreen, Svalbard. M.Sc. Thesis, Oulu University.
- Richardson-Näslund C (2001) Spatial distribution of snow in Antarctica and other glacier studies using ground-penetrating radar. Ph.D. Thesis, Thesis in Geography with emphasis on Physical Geography, 18. Stockholm University.
- Schytt V (1969) Some comments on glacier surges in eastern Svalbard. *Canadian Journal of Earth Sciences* 6, 4, part 2: 867-873.
- Sihvola A, Nyfors E & Evans S (1985) Mixing formulae and experimental results for the dielectric constant of snow. *Journal of Glaciology* 31, 108:163-170.
- Stenson BO (1951) Radar methods for the exploration of glaciers. Ph.D. Thesis, California Institute of Technology, Pasadena, CA, USA.
- Waite AH & Schmidt SJ (1962) Gross errors in height indication from pulsed radar altimeters operating over thick ice and snow. *Proceedings of the Institute of Radio Engineers*, 50, 6; 1515-1520.
- Watts RD, England AW, Vickers RS & Meier MF (1975) Radio-echo sounding on South Cascade Glacier, Washington, using a long-wavelength, mono-pulse source. *Journal of Glaciology*, 15, 73: 459-461.
- Winther J-G, Bruland O, Sand K, Killingtveit Å & Marechal D (1998) Snow accumulation distribution on Spitsbergen, Svalbard, in 1997. *Polar Research* 17, 2: 155-164