

The thermal regime of sub-polar glaciers mapped by multi-frequency radio-echo sounding

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ABSTRACT. Radio-echo soundings provide an effective tool for mapping the thermal regimes of polythermal glaciers on a regional scale. Radar signals of 320–370 MHz penetrate ice at sub-freezing temperatures but are reflected from the top of layers of ice which are at the melting point and contain water. Radar signals of 5–20 MHz, on the other hand, see through both the cold and the temperate ice down to the glacier bed. Radio-echo soundings at these frequencies have been used to investigate the thermal regimes of four polythermal glaciers in Svalbard: Kongsvegen, Uvérsbreen, Midre Lovénbreen and Austre Brøggerbreen. In the ablation area of Kongsvegen, a cold surface layer (50–160 m thick) was underlain by a warm basal layer which is advected from the temperate accumulation area. The surface ablation of this cold layer may be compensated by freezing at its lower cold-temperate interface. This requires that the free water content in the ice at the freezing interface is about 1% of the volume. The cold surface layer is thicker beneath medial moraines and where cold-based hanging glaciers enter the main ice stream. On Uvérsbreen the thermal regime was similar to that of Kongsvegen. A temperate hole was found in the otherwise cold surface layer of the ablation area in a surface depression between Kongsvegen and Uvérsbreen where meltwater accumulates during the summer (near the subglacial lake Setevatnet, 250 m a.s.l.). Lovénbreen was frozen to the bed at the snout and along all the mountain slopes but beneath the central part of the glacier a warm basal layer (up to 50 m thick) was fed by temperate ice from two cirques. On Austre Brøggerbreen, a temperate basal layer was not detected by radio-echo soundings but the basal ice was observed to be at the melting point in two boreholes.

INTRODUCTION

The glaciers in Svalbard are classified as polythermal (Sverdrup, 1935; Schytt, 1969; Liestøl, 1977a, 1988). On small glaciers, the winter cold wave is usually not eliminated and permafrost penetrates some distance into the ice and even into the bed beneath the ice mass. Surface meltwater drains supraglacially and only locally reaches the englacial and subglacial drainage system through crevasses and moulins. The situation is different

on large glaciers with accumulation areas at higher altitudes where the annual snow covers are thicker (see also Hooke and others, 1983). There, accumulation areas are frequently at the pressure-melting point down to the bed, except for a thin surface layer which reaches a thickness of a few metres during winter. The thick annual snow cover insulates against the winter cold wave which cannot penetrate beyond the firn layer. Furthermore, the snow is soaked with water during the summer and the heat capacity of this water prevents freezing below 10 m

during the winter. During summer, the winter cold wave is eliminated due to the latent heat released from refreezing of meltwater in the firn. In the ablation area, warming of the solid ice must take place through heat conduction, which is insufficient to eliminate the cold wave, and there the glaciers in Svalbard are commonly frozen to their beds near the sides and snout. However, down-glacier from temperate accumulation areas, a cold surface layer may be underlain for some distance by a core of warm ice which has been transported downward from the accumulation area. On the other hand, temperate basal layers in Arctic glaciers are not always advected from the accumulation area but may be created in situ by the heat of deformation (Blatter, 1985; see Paterson, 1994, p. 227–31). In many of the glaciers, the thermal conditions may have been affected by surges, which are believed to have occurred on about 90% of the glaciers in Svalbard (Liestøl, 1988).

Information on the thermal regime of Svalbard glaciers has been obtained from several sources. First, hydrological characteristics reflect the thermal regime of glaciers. Basal meltwater from temperate accumulation areas drains as ground-water beneath the permafrost or finds its way along the glacier bed beneath the frozen tongue. In winter, this meltwater forms icing on lowlands in front of glaciers terminating on land. However, near the fronts of tide-water glaciers it forms thick fjord ice, due to the upwelling of fresh water (Liestøl, 1977a, 1988). Secondly, temperature measurements have been carried out in boreholes, both in the surface layer (Sverdrup, 1935) and down to the bedrock (Kotlyakov and Macheret, 1987; Hagen, 1992, unpublished data). Thirdly, recent reports suggest that radio-echo sounding may provide an effective tool for mapping thermal conditions in sub-polar glaciers on a regional scale. Strong internal reflections of electromagnetic waves of very high (VHF, 35–60 MHz) and ultra-high frequencies (UHF, 440–620 MHz) have been interpreted as originating at an interface between cold ice and temperate ice containing liquid-water inclusions (Macheret and Zhuravlev, 1985; Bamber, 1987; Kotlyakov and Macheret, 1987; Glazovsky and Moskalevsky, 1989; Holmlund and

Eriksson, 1989; Vasilenko and others, 1990). The present paper, which adds further evidence for this, contains results of radio-echo sounding and from monitoring of temperatures in boreholes. Four glaciers in the Kongsfjord area (Fig. 1) were sounded in 1990 by ultra-high-frequency radar (UHF, 310–370 MHz) to detect internal reflections, as well as by a high-frequency radar (HF, 5–20 MHz) to map the bed topography. Similar radio-echo sounding was carried out by one of the authors (S.-E.H.) on Erikbreen in northern Spitsbergen in 1991 (Ødegård and others, 1992).

SITE DESCRIPTION

The four glaciers investigated are situated in the Kongsfjord area in northwest Spitsbergen at 78° 50' N and 12° E (Figs 1, 2, 3 and 4). The characteristics of these glaciers have been described by several authors during the last three decades, as summarized in Table 1. The geometry of the glaciers is known from surface maps and radio-echo sounding (Pillewitzer, 1967; Norsk Polarinstittutt, 1979; Macheret and Zhuravlev, 1982; Dowdeswell and others, 1984a, b; Hagen and Sætrang, 1991; Melvold, 1992, personal communication, 1994). Balance velocities and measured velocities are from Voigt (1965, 1967) and Hagen and Liestøl (1990). At the neighbouring coastal weather station in Ny Ålesund (42 m a.s.l.; in operation since 1975), the mean annual temperature is -6°C, the average from October through April is -12°C, and the July average is 5°C. The mean annual precipitation is about 370 mm (Steffensen, 1982; communication from The Norwegian Meteorological Institute, 1995).

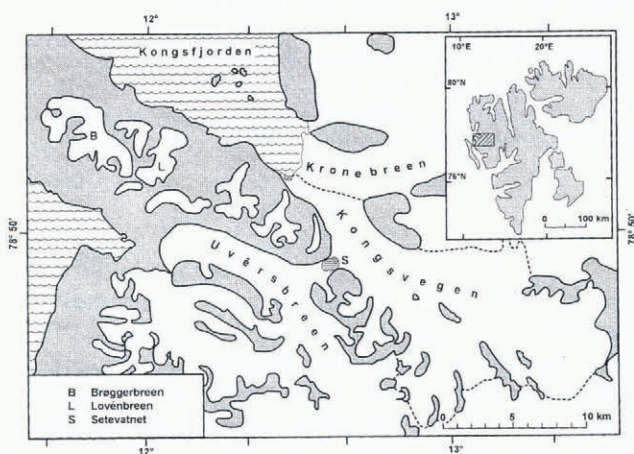


Fig. 1. Index maps of Svalbard showing the glaciers investigated: Kongsvegen, Uvørsbreen, Midre Lovénbreen and Austre Brøggerbreen.

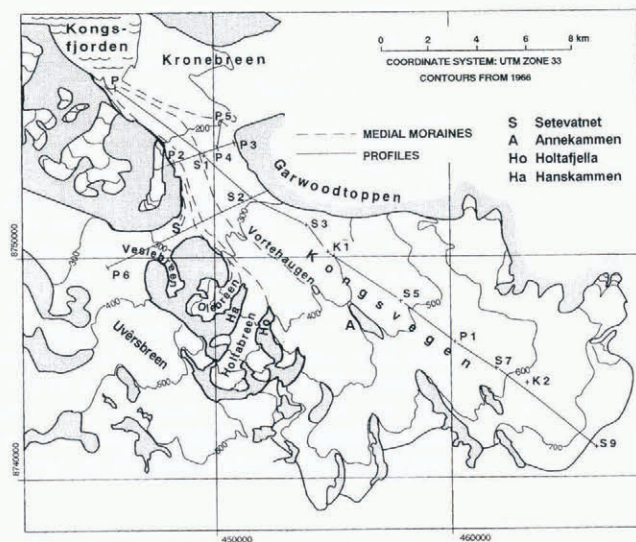


Fig. 2. Radio-echo sounding lines on Kongsvegen and Uvørsbreen. Surface elevation from Pillewitzer (1967).

Kongsvegen is a tide-water glacier with a shallow surface slope, draining an ice field into Kongsfjord. This glacier is temperate in its extensive accumulation area and water emerges throughout the year in channels at the calving front. In the ablation area, temperatures at 15 m depth are a few degrees below freezing, ice is frozen to the

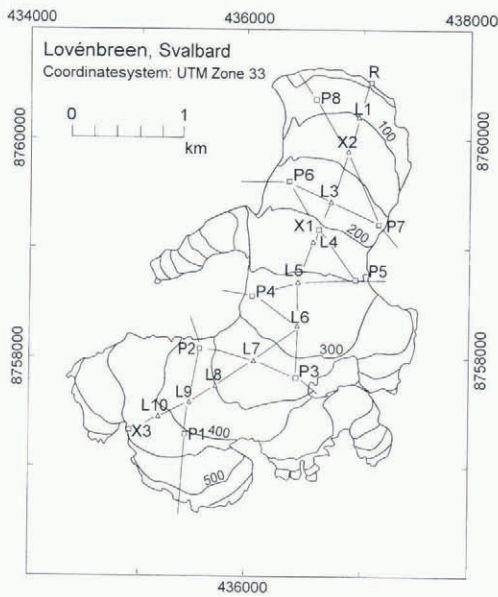


Fig. 3. Radio-echo sounding lines on Midre Lovénbreen. Surface elevation mapped in 1977 (from Norsk Polar-institutt, 1979); ELA = 400 m a.s.l.

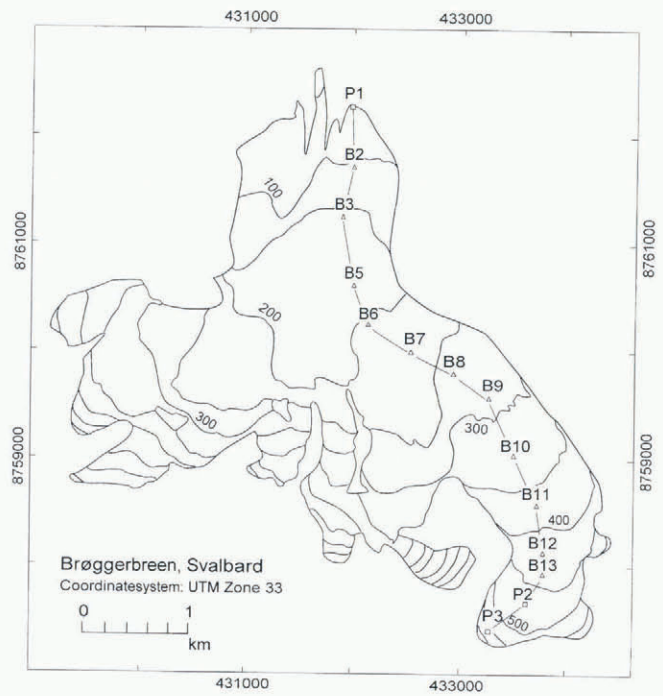


Fig. 4. Radio-echo sounding lines on Austre Brøggerbreen. Surface elevation mapped in 1977 (from Norsk Polar-institutt, 1979); ELA = 420 m a.s.l.

bed along the mountain sides (Liestøl, 1988) and meltwater is drained supraglacially in large rivers. Kongsvegen's velocity is much lower than the balance velocity and it is presumably heading towards a surge. The last surge was in 1948 (Liestøl, 1988) and since then the glacier surface has been lowering in the ablation area (e.g. about 1 m a^{-1} at about 200 m elevation), whereas it has been thickening in the accumulation area.

Uvérsbreen is a large valley glacier terminating on land. It is temperate in the accumulation area but the winter cold wave is not eliminated in the ablation area. No measurements of mass balance or velocity are available for this glacier.

Midre Lovénbreen, is an alpine-type valley glacier. Its accumulation area is about 30% of the total area. The winter cold wave is eliminated during the summer in two cirques in its uppermost parts, where the accumulation

rates exceed 3 m of snow. Elsewhere, temperatures at 15 m depth are below freezing and meltwater is partly drained supraglacially during the summer. Large masses of icing are observed in front of the glacier during the winter. Lovénbreen surged in the period between 1860 and 1880 (Liestøl, 1988) but its present velocity is equal to the balance velocity.

Austre Brøggerbreen is the thinnest of the four glaciers and the accumulation area is only about 20% of its total area. The winter accumulation is lower than on Lovénbreen, bare ice is observed even in the uppermost parts and the winter cold wave is not eliminated. The supraglacial drainage of meltwater during the summer is similar to that of Lovénbreen but the glacier does not

Table 1. Characteristics of Kongsvegen (K), Uvérsbreen (U), Midre Lovénbreen (L) and Austre Brøggerbreen (B), Spitsbergen

	<i>A</i> km ²	<i>d</i> m	<i>L</i> km	<i>z</i> ₀ m	<i>z</i> _m m	ELA m	<i>AAR</i>	<i>b</i> _w ma ⁻¹	<i>b</i> _s ma ⁻¹	<i>b</i> _n ma ⁻¹	<i>U</i> _b ma ⁻¹	<i>U</i> ma ⁻¹
K	102	440	25	20	850	490 (400–570)	0.75	0.82	0.71	0.10	20	5
U	60	360	20	50	800	≈500	0.75					
L	5.5	180	6	50	650	395 (225–650)	0.35	0.75	1.08	-0.33	4.5	4.5
B	6.1	130	7	60	650	413 (200–650)	0.18	0.72	1.14	-0.42	3	1.5

A, glacier area; *d*, maximum depth; *L*, length of glacier; *z*₀, surface elevation of the front; *z*_m, highest elevation of the glacier; ELA, mean equilibrium-line altitude (minimum and maximum altitudes in parentheses); *AAR*, accumulation area divided by total glacier area; *b*_w, winter balance; *b*_s, summer balance; *b*_n, net balance; *U*_b, balance velocity at ELA; *U*, measured velocity at ELA.

Mass balance, ELA and *AAR* for Midre Lovénbreen and Austre Brøggerbreen are from the period 1967–91, and for Kongsvegen from 1986 to 1994 (Hagen and Liestøl, 1990; Hagen and others, 1993; personal communication from K. Melvold, 1995).

drain meltwater during the winter. In a borehole in front of Brøggerbreen, permafrost has been encountered down to 140 m (Liestøl, 1988). The low velocity of Brøggerbreen may indicate that it is a surging glacier but, during the past 20 years, its mass balance may have been too negative to build up to a surge. It last surged in about 1890 (Liestøl, 1988). In the period 1912–88 the glacier lost about 34 m of water, averaged over its entire area, which corresponds to almost 30% of its volume of 1912 (Lefauconnier and Hagen, 1990). The average thinning of Lovénbreen has been only slightly lower (Hagen and Liestøl, 1990). For these two glaciers to be in mass balance with their present volume and area, the equilibrium line would have to be about 100 m lower than at present.

METHODS

A range-gated synthetic-pulse radar system was used for sounding the glaciers (Hamran, 1989; Hamran and Aarholt, 1993; Hamran and others, in press). The radar system is able to cover frequencies from 0.1 MHz to 3 GHz but the band width is adjustable, depending on the characteristics of the antennae; 201 equidistant steps of frequency were collected over the band width given by the applied antennae. Two antenna types were used, giving sub-surface information at two different wavelengths. For bedrock mapping, a non-resonant (resistively loaded) dipole antenna was used, operating from 5–20 MHz (Watts and England, 1976; Watts and Wright, 1981). A band width of 15 MHz and frequency steps of 75 kHz gave a range resolution in ice of 5.6 m. Secondly, for sounding the internal structure of the glacier, a UHF radar system with Yagi antennae was used, with six elements and an opening angle of 60°. This covered the frequency range of 320–370 MHz with steps of 250 kHz, giving a range resolution in ice of 1.7 m. The transmitted power per frequency was 1 W, producing a synthetic peak power of 200 W. The integration band width at each frequency was 3 kHz, thus giving low thermal noise.

The radar data were collected and stored on a portable computer giving quick-look data in the field. The data were processed using inverse Fourier fast transform to compute the time domain signal and displayed as intensity-modulated plots with a linear magnitude scale. The radar system was operated from sledges pulled by a snowmobile. The antennae were spaced approximately 2.5 m apart on a glass-fibre rod attached to the sledge in a transverse position about 0.5 m above the snow surface. The sampling of the echo sounder was controlled by a wheel attached to the sledge, conveying triggering pulses to the computer. The radar was moved along the glacier surface at a speed of about 20 km h⁻¹ and measurements were taken at an interval of every 4.2 or 8.4 m. Power was supplied by a 1500 W Honda generator. Positioning on the glacier was obtained by referring to a grid used for mass-balance measurements.

The velocity of the radar waves was taken as 167 m μ s⁻¹. No corrections were made for the presence of a firn layer, because it is only 20–30 m thick at its maximum, and the errors thus introduced in estimated depths are relatively small. The reflection profiles were deconvoluted

to bedrock profiles following procedures similar to those used in seismic migration (see Harrison, 1970). The accuracy of estimates of ice depths by the HF radar is considered to be ± 15 m or 2% and by the UHF radar ± 5 m.

The radio-echo soundings were carried out during the period 19–25 May 1990 before melting had started. The locations of the sounding lines are shown in Figures 2, 3 and 4.

RADAR RECORDS SUGGESTING THERMAL LAYERING

In the ablation areas of Kongsvegen and Lovénbreen, the UHF radar (320–370 MHz) was only able to penetrate the surface layer of sub-freezing temperatures (Figs 5 and 6). Its range was limited by an internal reflecting interface which was located close to the top of a basal layer of ice which was at the melting point. In a borehole at K1 on Kongsvegen (Fig. 2), the glacier was at the pressure-melting point below about 80 m depth (Fig. 7) and at that site internal reflections were observed at 90 (± 5) m depth (Fig. 5).

The UHF radar waves were totally reflected in the wet surface layer of the accumulation area of Kongsvegen. Indeed, between holes K1 and K2 the internal reflecting interface disappeared suddenly at about 60 m depth without any gradual transition to the surface (Fig. 5a). This occurred at an elevation of about 450 m, which is the lowest equilibrium-line elevation over the last 8 years (in 1987). A similar abrupt disappearance of the internal reflection (at 60 m depth) has been observed on the neighbouring Uvérsbreen (unpublished data), whereas a very steep interface could be traced on Erikbreen in northern Spitsbergen (Ødegård and others, 1992). (The same echo sounder was used in all three studies.) Therefore, further attention must be paid to the thermal layering of the superimposed ice in the transition zone between the accumulation and ablation areas of glaciers in Svalbard and to the potential of VHF and UHF radars to map these conditions.

On Lovénbreen, a temperate basal layer was encountered at about 100 m depth (Fig. 7) and at that site an internal scattering interface was observed at 105 (± 5) m depth (at site L9, 3.5 km from the front; Fig. 3). In a borehole farther down-glacier (at L3), the ice was at the pressure-melting point at about 110 m depth, which again corresponds to the depth of the scattering interface. Internal reflections were not seen on Austre Brøggerbreen, although the melting point was reached in boreholes close to the bed (Fig. 7), nor were they observed in the lowest 0.5 km of the snout of Lovénbreen.

The location of the internal reflecting interface close to the depths where the ice is at the pressure-melting point suggests that the UHF radio waves were scattered from the top of a layer containing liquid-water inclusions (cf. Smith and Evans, 1972; Watts and England, 1976). This is in agreement with results obtained on Fridtjofbreen using airborne echo sounding at 620 MHz and borehole temperature measurements (Kotlyakov and Macheret, 1987, p.157). Furthermore, Bamber (1987) has also advanced this explanation of internal reflecting layers, recorded at 60 MHz radar frequency in Svalbard glaciers.

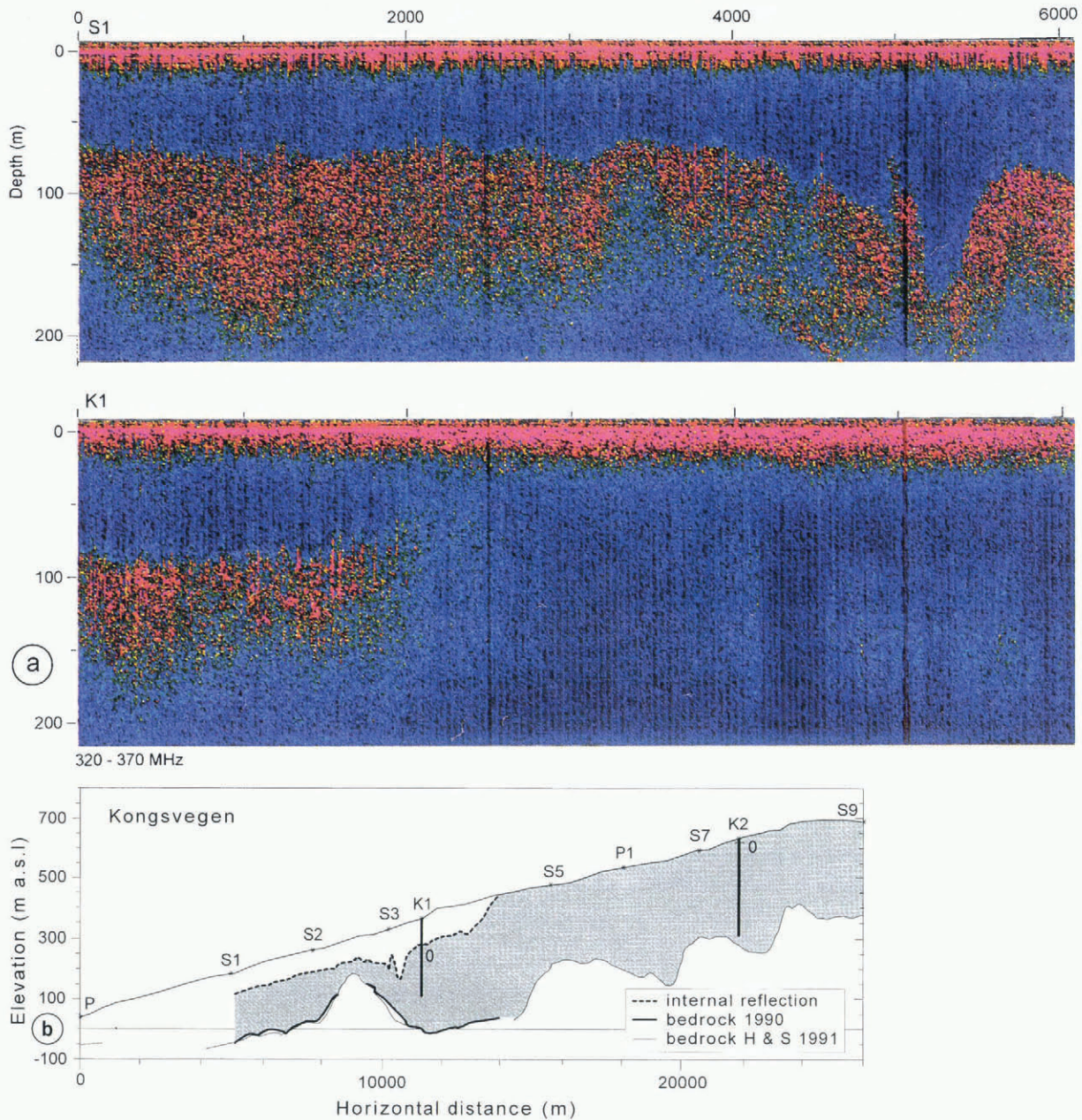


Fig. 5. Radio-echo soundings on Kongsvegen and their interpretation (see Figure 2 for location). (a) Intensity-modulated plot of internal reflections of UHF radar (320–370 MHz). Distance is measured from S1, 5 km from the calving front. The uppermost red lines show ringing in the antennae and the lower red zone shows internal reflections from temperate ice. The internal reflections are not seen in the accumulation area where the energy is totally reflected in the wet surface layer (see discussion in the text). (b) Longitudinal profile showing interpretation of radio-echo soundings. The shaded area is temperate ice. K1 and K2 show the locations of boreholes in which temperature profiles were measured. Bedrock topography was obtained from our HF radar (5–20 MHz) and from a map by Hagen and Sætrang (1991). Bedrock elevation at the calving front is from Elverhøi and others (1980) and glacier-surface elevation is from Melvold (1992, personal communication, 1994).

Thus, in the following description we assume that the UHF radar recorded the interface between a cold surface layer and a temperate basal layer.

THE THERMAL REGIME OF GLACIERS OF THE KONGSFJORD AREA

Kongsvegen

In the ablation area of Kongsvegen, a temperate basal

layer is overlain by ice of sub-freezing temperatures (Figs 5 and 6). The cold surface layer increased in thickness up-glacier from about 60 to 90 m. Over a distance of about 600 m on both sides of S3 (Fig. 2), where the sounding line approaches the mountain Garwoodtoppen, the cold surface layer dipped still deeper (down to 160 m in a 200 m long section; Fig. 5). Furthermore, the cold layer was found to be thicker beneath medial moraines than in their surroundings (Fig. 6). One such medial moraine originates from the nunatak Vortehaugen, another from a mountain ridge separating two outlets draining north-

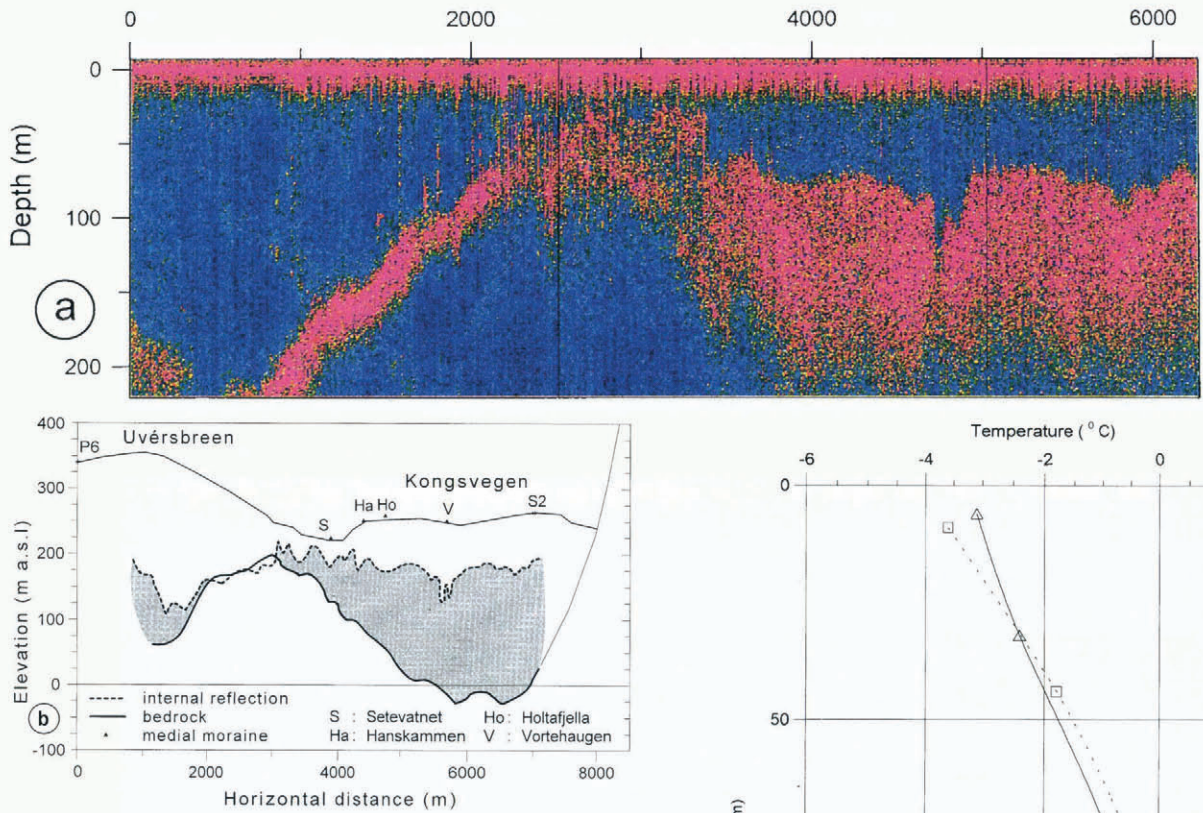
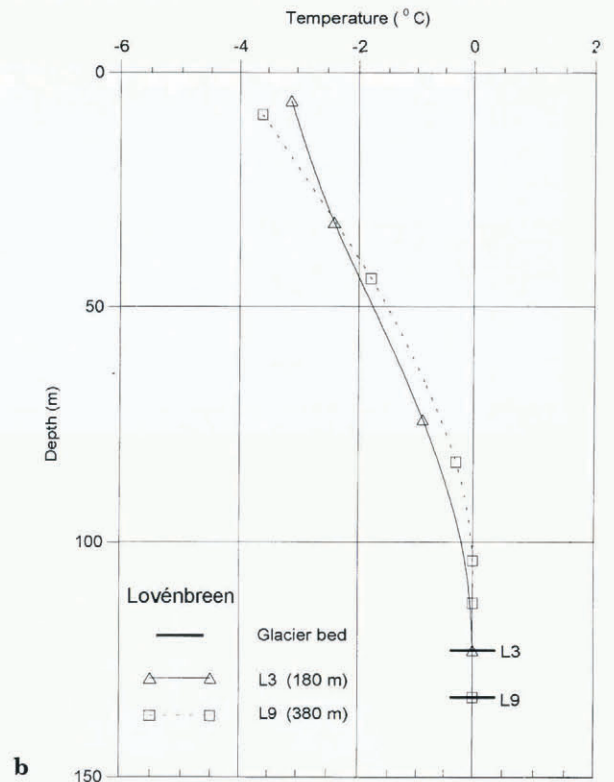
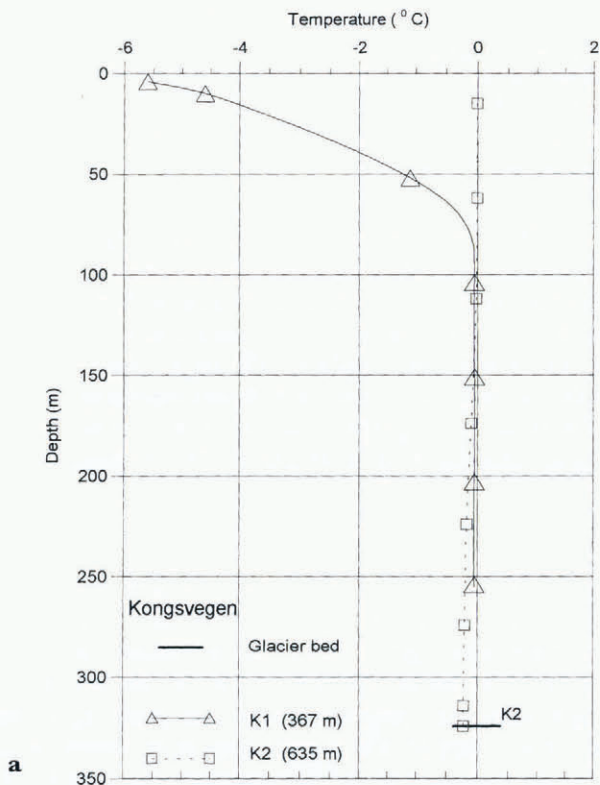
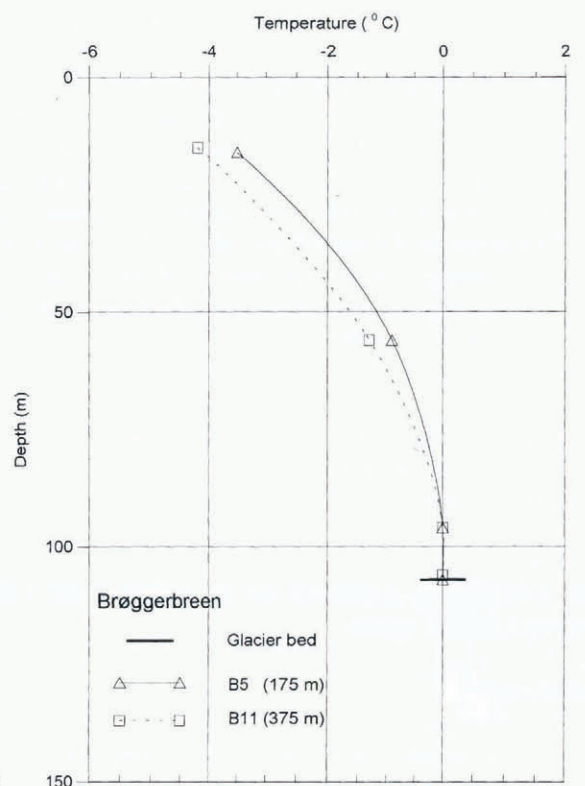


Fig. 6. Radio-echo soundings along a transverse section on Kongsvegen to Uvørsbreen from S2 to P6 (Fig. 2) and their interpretation. (a) Intensity-modulated plot of reflections of UHF radar system. (b) Interpretation of radio-echo soundings. Glacier surface elevation is based on data from Melvold (1992, personal communication, 1994) and outside the glacier from Pillewitzer (1967).



b



c

Fig. 7. Temperature profiles from boreholes on Kongsvegen, Midre Lovénbreen and Austre Brøggerbreen (from Hagen (1992)). For location see Figures 2, 3, 4 and 11. Glacier-surface elevation is given in parenthesis.

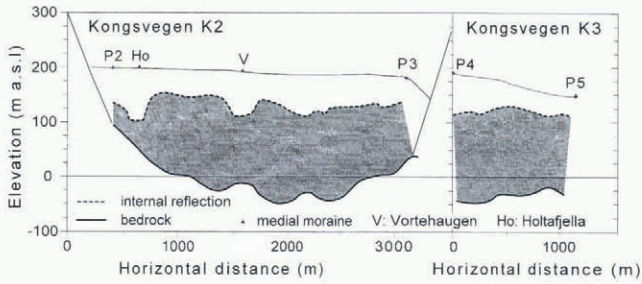


Fig. 8. Interpretation of radar reflections along transverse sections of Kongsvegen, P2 to P3 and P4 to P5 (see Fig. 2).

wards from Holtafjella, the third from Hanskammen and the fourth from the Setevatnet area (Fig. 2). At all these locations, the glacier is below the pressure-melting point to a considerable depth along the mountain walls, where ice is moving slowly and the cold wave has had a longer time to penetrate than in the central parts of the glacier.

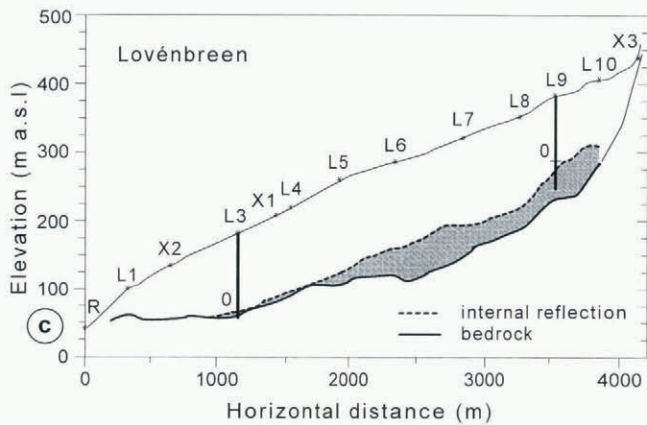
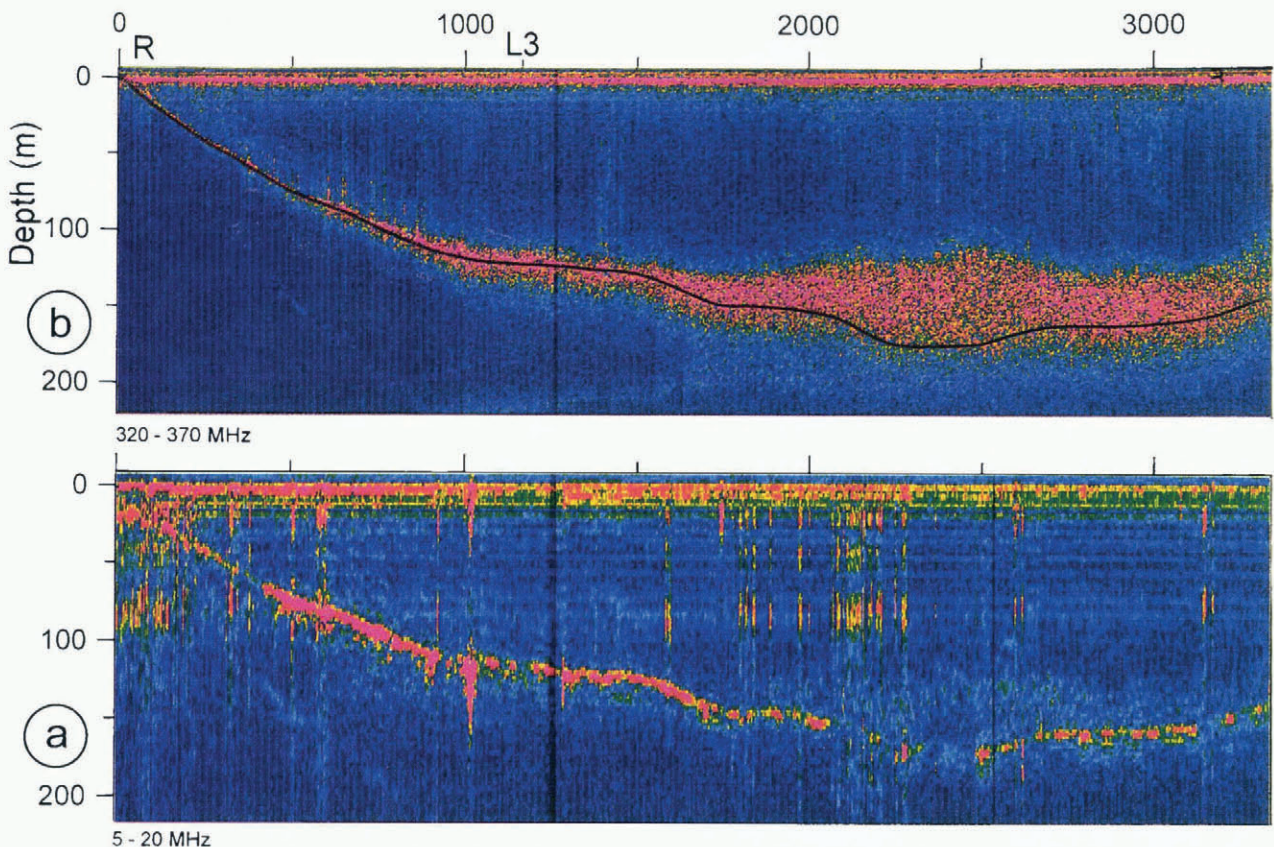


Fig. 9. Radio-echo soundings on Lovénbreen and their interpretation. (see Figure 3 for location). (a and b) Intensity-modulated plots of radar reflections. The heavy solid line on the UHF radar (320–370 MHz) shows the bedrock as sounded by the HF radar (5–20 MHz). The lower boundary of the scattering UHF record does not define the bedrock but delayed returns from discrete scatters on the rough bed. (c) Interpretations of radar reflections along a longitudinal profile (R to X3). The shaded area is temperate ice. L3 and L9 show the location of the boreholes where temperature profiles were measured. Glacier-surface elevation is from a map from Norsk Polarinsitutt (1979).

This explains why the medial moraines are located above the centre line of these depressions of cold ice. Along a transverse profile at about 200 m surface elevation (P2 to P3; Fig. 8), the cold layer is depressed from 50 m down to 90 m at the Holtafjella moraine and 70 m at the Vortehaugen moraine. Higher in the ablation area, at about 250 m elevation, the cold surface layer is depressed from 60 to 75 m and 100–110 m, respectively, beneath these two moraines (Fig. 6b).

The cold surface layer is only 10–30 m thick over a distance of 1 km in the saddle between Kongsvegen and Uvérsbreen (Fig. 6). Surface meltwater is drained to the centre of this depression and accumulated in the supra- and subglacial lake Setevatnet (Liestøl, 1977b). The lake drains regularly in jökulhlaups, thus maintaining crevasses in the area which are partly filled with water during the summer. Over some distance within this area we would expect the cold surface layer to be eliminated during the summer.

Farther up-glacier, Kongsvegen is at the melting point



over its entire depth (Figs 5a and 7). The radar reflections suggest that this may be up-glacier from a surface elevation as low as 450 m but further investigations should be carried out to study the temperature conditions in this zone where the equilibrium line is fluctuating from year to year.

The cold surface layer of Kongsvegen has been melting on the surface at an average rate of 0.65 m a^{-1} over the period 1987–94 (personal communication from K. Melvold, 1995). This reduction in the thickness of the cold layer may be compensated by freezing at its lower boundary. At the site K1, the freezing rate would equal the observed surface ablation of 0.8 m a^{-1} (over 30 years) if the free water content in the ice at the freezing interface were about 1% of the volume; given the temperature gradient at the cold temperate interface of 0.04 K m^{-1} (Fig. 7), a thermal conductivity of ice of $2.1 \text{ W K}^{-1} \text{ m}^{-1}$, a latent heat of fusion of $3.0 \times 10^{-8} \text{ J m}^{-3}$ and estimating the vertical advection from an approximation of steady-state ice flow. At a similar internal reflecting interface in Fridtjovbreen in the Isfjord area of Spitsbergen, Kotlyakov and Macheret (1987) concluded from borehole studies that the water content in the ice was roughly 1–2%.

Uvérsbreen

On Uvérsbreen, a temperate basal layer is also overlain by ice at sub-freezing temperatures (Fig. 6). As the bed starts to slope from the Setevatnet area into the neighbouring valley which contains Uvérsbreen, the upper line of the UHF record coincides with the HF radar reflection from the bed. Therefore, the red zone on the UHF record is not interpreted as a temperate layer but rather as scattering from the bed. In this area ice drains from the small hanging glacier, Veslebreen (Fig. 2), judged to be cold-based from this observation.

Lovénbreen

On Lovénbreen a temperate basal layer is situated in the central upper part of the glacier (Figs 9 and 10). This ice originates from the cirques on either side of the glacier, where the cold wave is eliminated (unpublished observations by O. Liestøl). The existence of a temperate accumulation area in the eastern cirque can also be anticipated by extrapolating the internal-reflection line eastward from P1 in Figure 10. Except for these cirques, the glacier is frozen to the bed along all the mountain slopes and presumably also along the entire bed in the lowest 1 km of the snout. The cold surface layer penetrates deeper into the glacier along the western than the eastern side because the winter accumulation is reduced along the western mountain wall due to snowdrift.

Austre Brøggerbreen

No internal scattering was detected by the UHF radar on Austre Brøggerbreen (Fig. 11), although the scattering of the UHF reflections increased somewhat in the up-glacier direction (i.e. scattering from the bed). As the winter cold wave is not eliminated in the accumulation area of this glacier, temperate basal ice is presently not advected from the glacier surface. Measurements in two boreholes (Fig. 7),

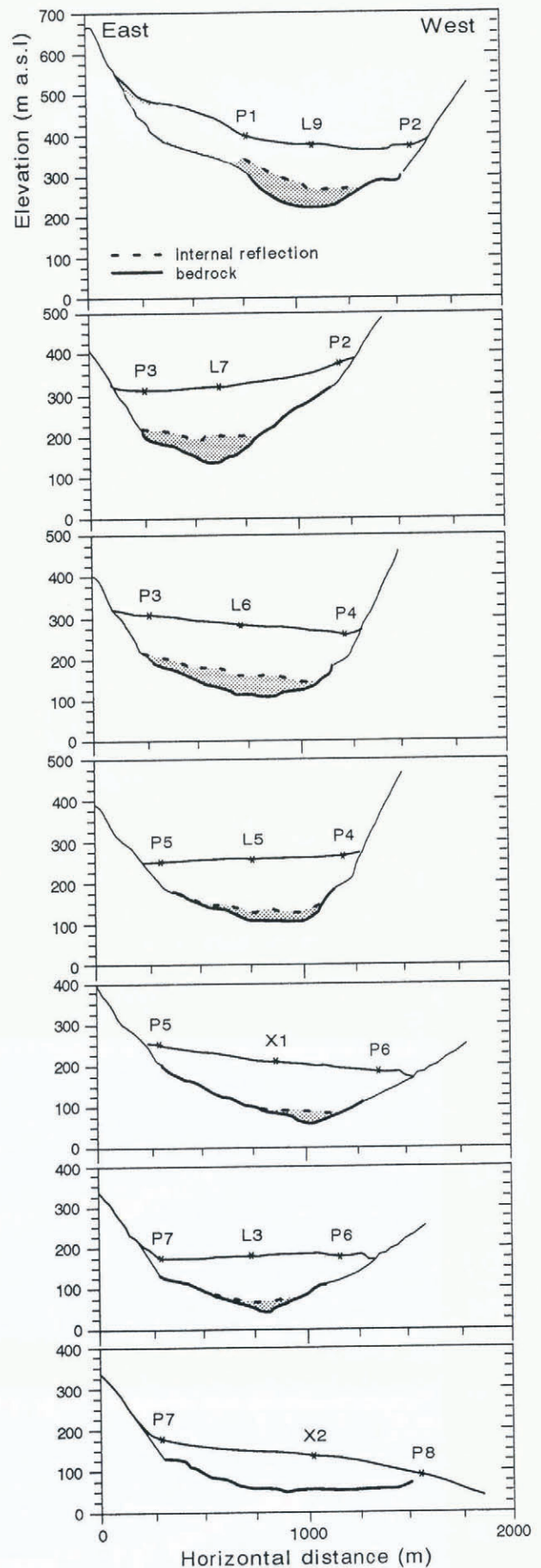


Fig. 10. Interpretations of radar reflections along transverse sections of Lovénbreen (see Figure 3 for location of profiles). The shaded area is temperate ice.

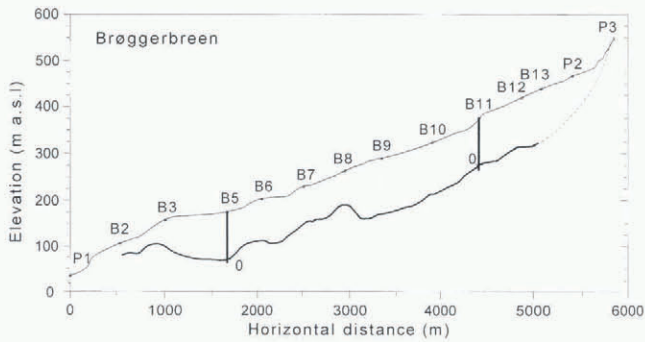


Fig. 11. Interpretation of UHF-radar reflections (320–370 MHz) along a longitudinal profile (P1 to P3) of Austre Brøggerbreen (see Fig. 4).

however, showed ice at the melting point on the glacier bed, so a thin temperate basal layer may underlie the central part of the glacier.

CONCLUSIONS

Radio-echo sounding provides an effective tool for mapping thermal regimes of polythermal glaciers on a regional scale. On glaciers in Svalbard, internal reflections detected by UHF radars seem to be located at the top of a basal layer containing liquid-water inclusions. The reflecting surface is located close to depths where borehole measurements indicate that the ice is at the pressure-melting point. The UHF radar waves penetrate surface layers of sub-freezing temperatures but are totally reflected in wet surface layers of accumulation areas. However, a gradual transition of the internal reflecting interface could not be followed from the ablation area to the accumulation area. Rather, the interface disappeared abruptly at about 60 m depth. Further attention must be paid to the thermal layering in the transition zone between the accumulation and ablation areas of glaciers in Svalbard and to the potential of radars at various frequencies for describing these conditions.

In the ablation area of Kongsvegen, a surface layer of sub-freezing temperatures is underlain by a temperate basal layer. The surface ablation of this cold layer may be compensated by freezing at its lower cold-temperate interface. This requires that the free-water content in the ice at the freezing interface is about 1% by volume. The surface layer is thicker beneath medial moraines and where cold-based hanging glaciers enter the main ice stream. A temperate hole was found in the otherwise cold surface layer of the ablation area. This was in a surface depression between two adjacent ice streams where meltwater accumulates during the summer.

A layer of temperate ice was found beneath the central part of Lovénbreen. This ice originated from cirques on either side of the glacier. Elsewhere, the glacier is cold-based along the mountain slopes and presumably along the entire bed in the lowest 1 km of the snout. The cold surface layer penetrates deeper into the glacier where the winter accumulation is reduced due to snowdrifting.

Only a thin temperate basal layer exists beneath the central parts of Austre Brøggerbreen but at present no temperate ice is advected from the glacier surface.

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