Radio-echo soundings of sub-polar glaciers with low-frequency radar

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Air-borne radio-echo soundings of sub-polar glaciers in Svalbard have previously been carried out by Soviet scientists using high frequency radar units of 620 and 440 MHz. Later a British/Norwegian group made soundings with 60 MHz equipment. The high frequency radar units seemed to underestimate the ice thicknesses. The 60 MHz radar unit seemed to give more accurate results when compared to areas with gravity surveyed bed. However, both the Soviet and the British equipment seldom recorded bed-echoes in accumulation areas where firn soaking during summer and thus zero temperatures are likely to occur. A low-frequency impulse radar unit of 8 MHz, however, recorded bed echoes in these areas too. In the accumulation area of Kongsvegen depths down to 440 m were recorded. The glacier bed is thus close to sea level at approximately 12 km from the calving front. Soundings were carried out on Brøggerbreen, Lovénbreen and Kongsvegen. Subglacial maps were generated from the data. Internal reflections that were probably caused by englacial drainage channels could be observed. Frequent internal reflections close to the bed could be interpreted as an indication of temperate ice. However, we could not find any distinct upper level of these reflections.

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Soviet scientists were the first to carry out radio-echo soundings on glaciers in Svalbard. They used ultra high frequency (UHF) radar units of 440 MHz and 620 MHz. Most of their work was carried out from helicopters, but they also performed detailed oversnow soundings on selected glaciers (Macharet & Zhuravlev 1982). Scott Polar Research Institute (SPRI), England, and Norsk Polarinstitutt, Norway, carried out aerial soundings with very high frequency radar units (VHF) of 60 MHz in 1980 and 1983 (Dowdeswell et al. 1984a, b).

In most cases the UHF-equipment seemed to underestimate the ice thickness. The SPRI-system at 60 MHz recorded depths 2–3 times deeper on many glaciers (Dowdeswell et al. 1984a). Compared to different gravity-surveyed beds, the 60 MHz results seemed to be most correct, within ± 10%.

The thermal regimes of the glaciers in Svalbard are mostly subpolar, that is with large parts at the pressure melting point and other parts with negative temperatures (Sverdrup 1935; Liestøl 1976). The accumulation areas are usually at the melting point throughout due to firn soaking during the summer. The absorption and scattering of radio-signals by meltwater, soaked firn and ice lenses increase with radio frequency (Smith & Evans 1972). Dowdeswell et al. (1984a) suggest that this is probably the main reason why both the Soviet and the SPRI equipment seldom received any bed echoes from the accumulation

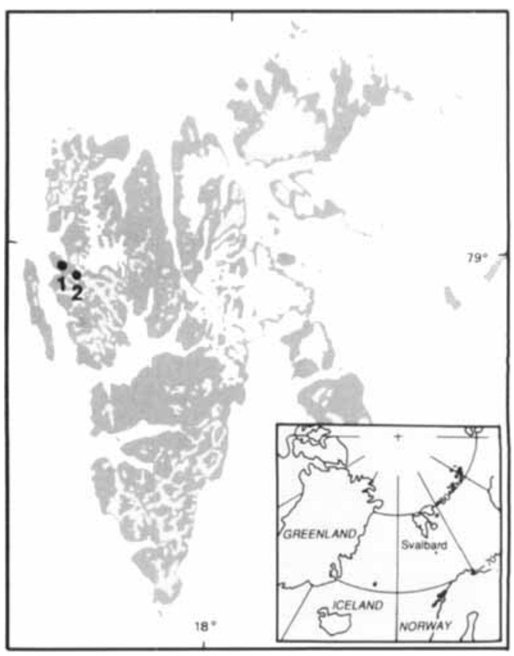

Fig. 1. Location map of Svalbard with the investigated glaciers. 1. Brøggerbreen and Lovénbreen. 2. Kongsvegen.

areas. Great parts of the glaciers were therefore not covered. Bamber (1987a, b, 1988, 1989) has also investigated problems of scattering from internal discontinuities in ice masses close to the melting point, and he uses Svalbard glaciers as examples. Dowdeswell et al. (1984a) recommended the use of radio-echo soundings below 10 MHz for bed sounding in the accumulation areas. Such low-frequency soundings have been carried out with success for many years on temperate glaciers, for example in Iceland and Sweden (Bjørnsson 1981, 1986) and in Norway (Sætrang & Wold 1986).

The aim of these investigations was therefore to test the low-frequency radar on Kongsvegen where the UHF and VHF radar missed the bed echo. Brøggerbreen and Lovénbreen were sounded in order to compare the results with former successful radio-echo soundings, gravity surveys and hot water drilling to the bed.

The locations of the investigated glaciers are shown in Fig. 1.

Methods

The radio-echo soundings presented here were carried out in the period 19–24 May 1988. The ablation season had not yet started, so the glaciers had minimum water content.

The radar unit was a MARK II, 8 MHz monopulse system described by Sverrisson et al. (1980).

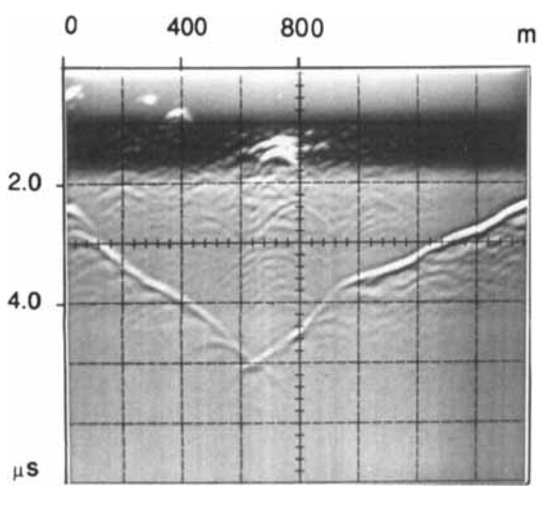

Fig. 2. Strong bed echoes were obtained from all investigated glaciers. Above is an example from Kongsvegen. Note the strong reflection hyperbola, probably from englacial channels.

The frequency window of the sounder was 0.1–10 MHz and the center frequency was 8 MHz. The receiver and the transmitter were placed on two sledges and towed behind a snow-scooter. The transmitter was placed in the center of the 14 m long dipole antenna on the second sledge. Sounding lines were found by compass and visual navigation from surveyed positions of ablation stakes on the glacier. The distances along the profiles were measured by an odometer wheel. The radio-echo signals were recorded on 35 mm negative film as A-mode pictures (echo-amplitude vs. time delay) at a few points and as Z-mode (intensity modulated) pictures along the profiles. A typical profile is shown in Fig. 2. The two-way travel time of the radio-pulse is represented by the vertical axis and the surface distance by the horizontal axis. The vertical depth of the ice was obtained by digitizing the photographic records. A radio-wave velocity of 169 m/μs in ice was used when the depth was calculated. The surface position and elevation were taken from digitized maps with scales of 1:100000 for Kongsvegen and 1:20000 for Lovénbreen and Brøggerbreen. The depth resolution of the reflected signal is 6 m, but due to uncertainties when digitizing the profiles the accuracy of the ice thickness is considered to be ± 10 m.

Radio-echo profiles

The radio-echo profiles covered a total distance of 136 km with 69 km on Kongsvegen (105 km^2), 38 km on Brøggerbreen (5.5 km^2) and 29 km on Lovénbreen (5.0 km^2).

A generally strong bottom return was also observed in the accumulation areas where firn soaking during the summer and thus zero temperatures are likely to occur. One of the authors (JOH) measured zero degrees Centigrade in the firn area of Kongsvegen in 1989 throughout a depth profile from the surface to the bottom at 330 m. In some places a multiple bottom return was observed. Internal reflections have not affected the interpretation of bottom reflectors. A profile from Kongsvegen crossing Setevatnet and continuing over Uværsbreen showed that there were considerably weaker bottom returns on Uværsbreen, which is believed to be approaching a new surge. The greatest depth sounded on Kongsvegen was 440 m, on Lovénbreen 178 m, and on Brøggerbreen 153 m.

Table 1. Comparison of radio-echo soundings to bore-hole depths.

Hole	Bore-hole depth (1)	Radar depth (m)				Mean (2)	std. dev.	Diff. 1–2
L3	123	117	113	113	100	111	7	+12
L9	133	139	143	147	—	143	4	−10
B5	108	117	105	99	—	107	9	+ 1
B11	106	113	105	105	102	106	5	0

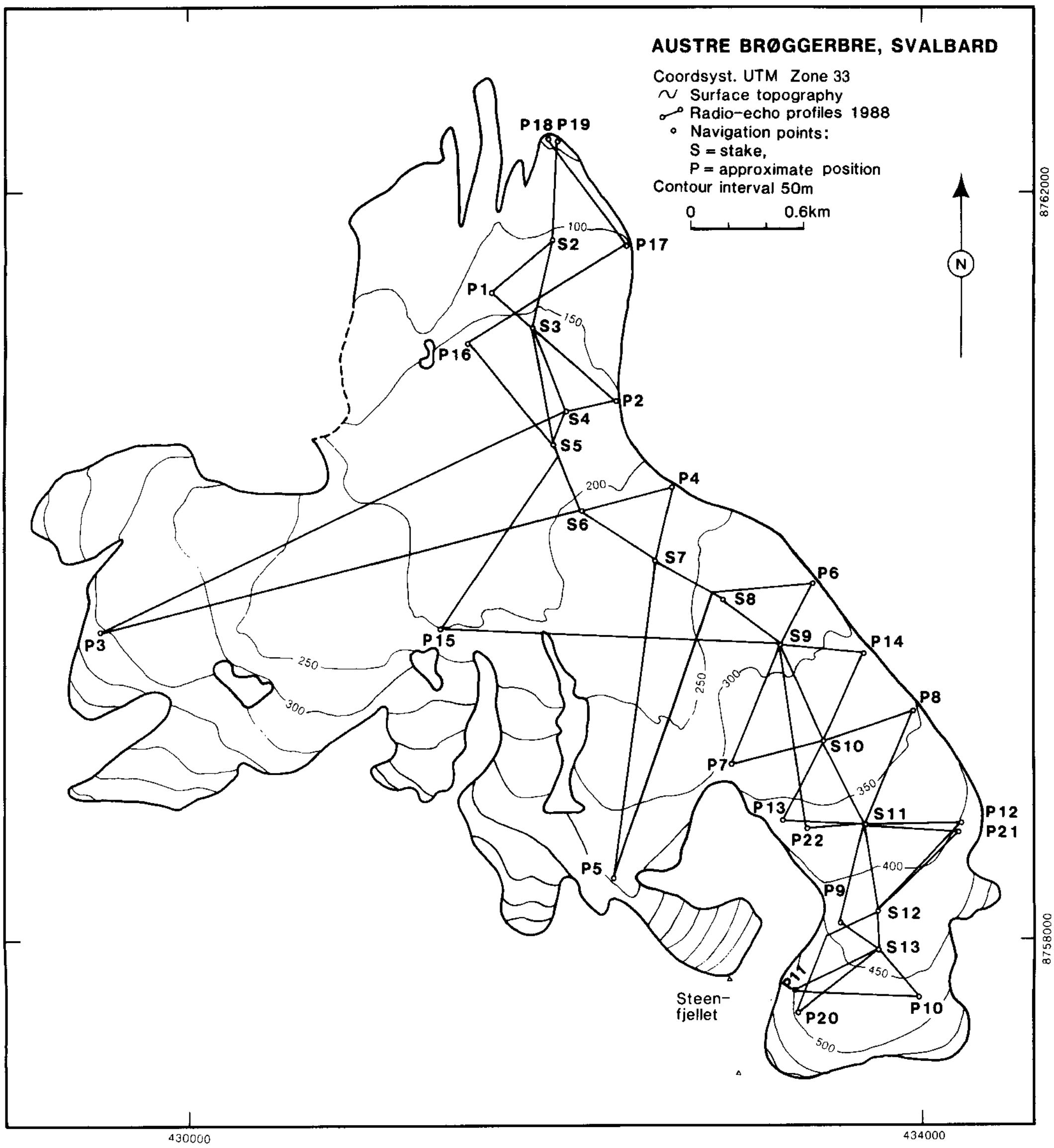

Fig. 3. Sounding lines on Brøggerbreen.

The sounding lines from the three investigated glaciers are shown in Figs. 3, 5, and 7. The density of the profiles is much less on Kongsvegen than on the other two glaciers. The density of bed points is thus lower, and the quality of the subglacial maps generated from the data sets is better on Brøggerbreen and Lovénbreen. The computer program SURFER has been used to interpolate and draw the subglacial maps from bed points calculated at 25 m intervals along the profiles. The subglacial topography maps together with the surface maps are shown in Figs. 4, 6, and 8. The subglacial map from Kongsvegen shows that bed elevation is close to sea level as far as 12 km from the glacier front. The bed contour interval is 50 m on Kongsvegen and the map shows some basin-like forms in the main valley. On Lovénbreen and Brøggerbreen, subglacial maps with

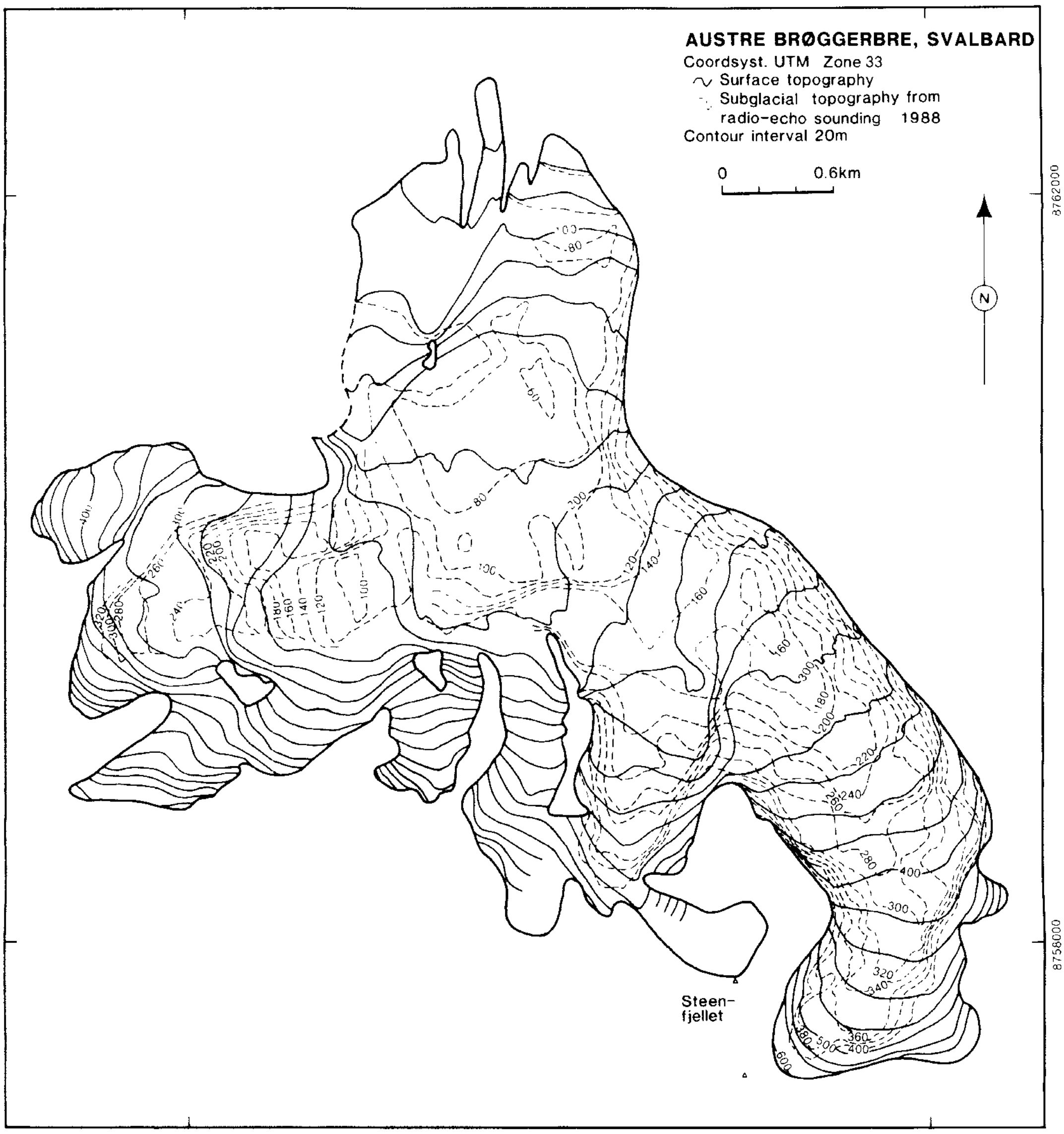

Fig. 4. Surface and subglacial topography for Brøggerbreen.

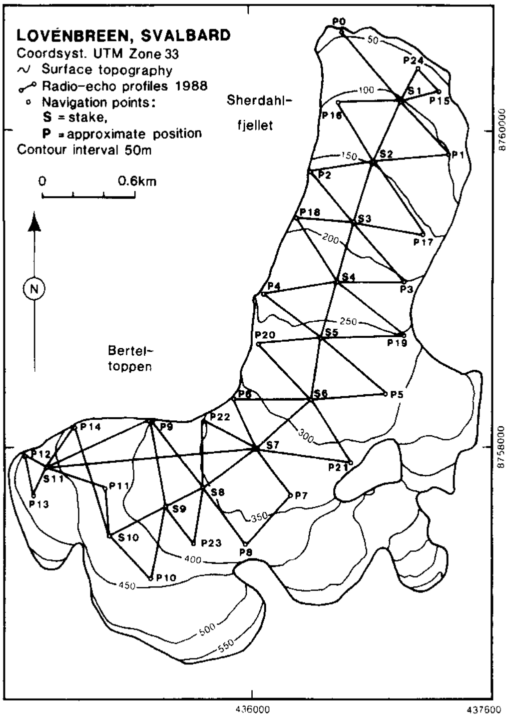

Fig. 5. Sounding lines on Lovénbreen.

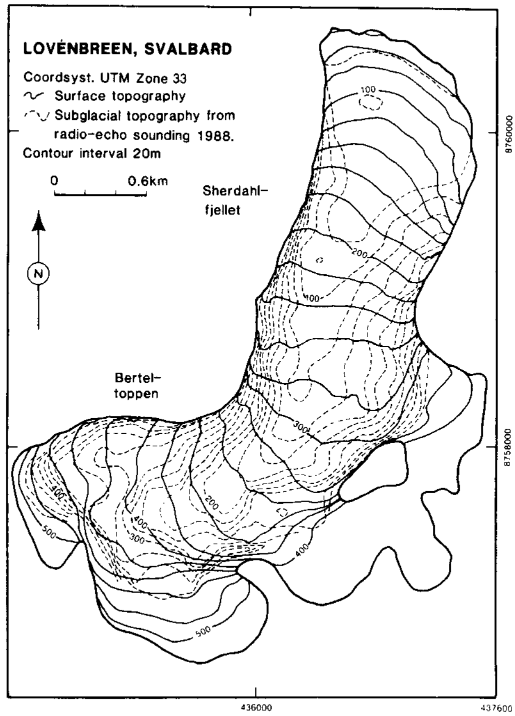

Fig. 6. Surface and subglacial topography for Lovénbreen.

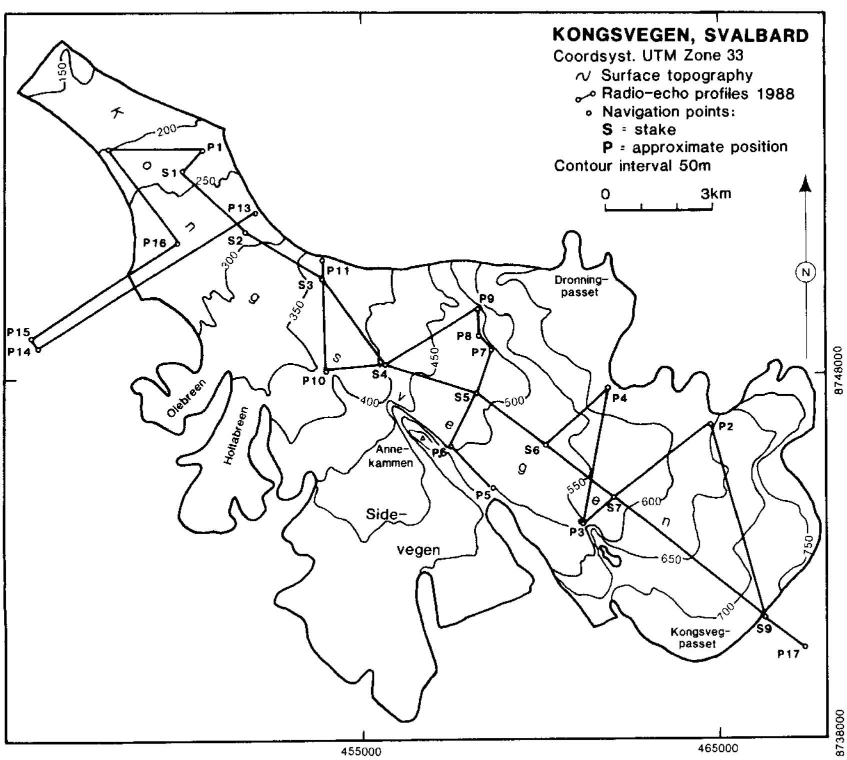

Fig. 7. Sounding lines on Kongsvegen.

contour intervals of 20 m were made. On Brøggerbreen the work was concentrated in the eastern part.

Comparison with former soundings

Both on Brøggerbreen and on Lovénbreen the 8 MHz equipment corresponded closely with former successful soundings made by both the Soviet 440 MHz and the SPRI 60 MHz systems. In Fig. 9 the longitudinal profiles on the two glaciers are seen together. The small discrepancies are probably caused by slightly different tracks along the centerline of the glaciers. Our length profiles have been drawn along a centerline as taken from the subglacial maps.

On Kongsvegen, however, both the Soviet 440 MHz and the British 60 MHz systems never received any bed echoes from the accumulation area during the former aerial soundings. From the ablation area they registered some bed echoes, but even there bed reflections were lacking over large areas. Our results were in agreement with those from the 60 MHz signals and the gravity-surveyed bed in the lower part of the glacier. The 440 MHz results, however, corresponded to the internal echoes from the 60 MHz system and have probably been misinterpreted as bed echo (Fig. 10), as suggested by Dowdeswell et al. (1984b).

Brøggerbreen is the only glacier of these three where a subglacial map has been produced before (Macheret 1976; Macheret & Zhuravlev 1982).

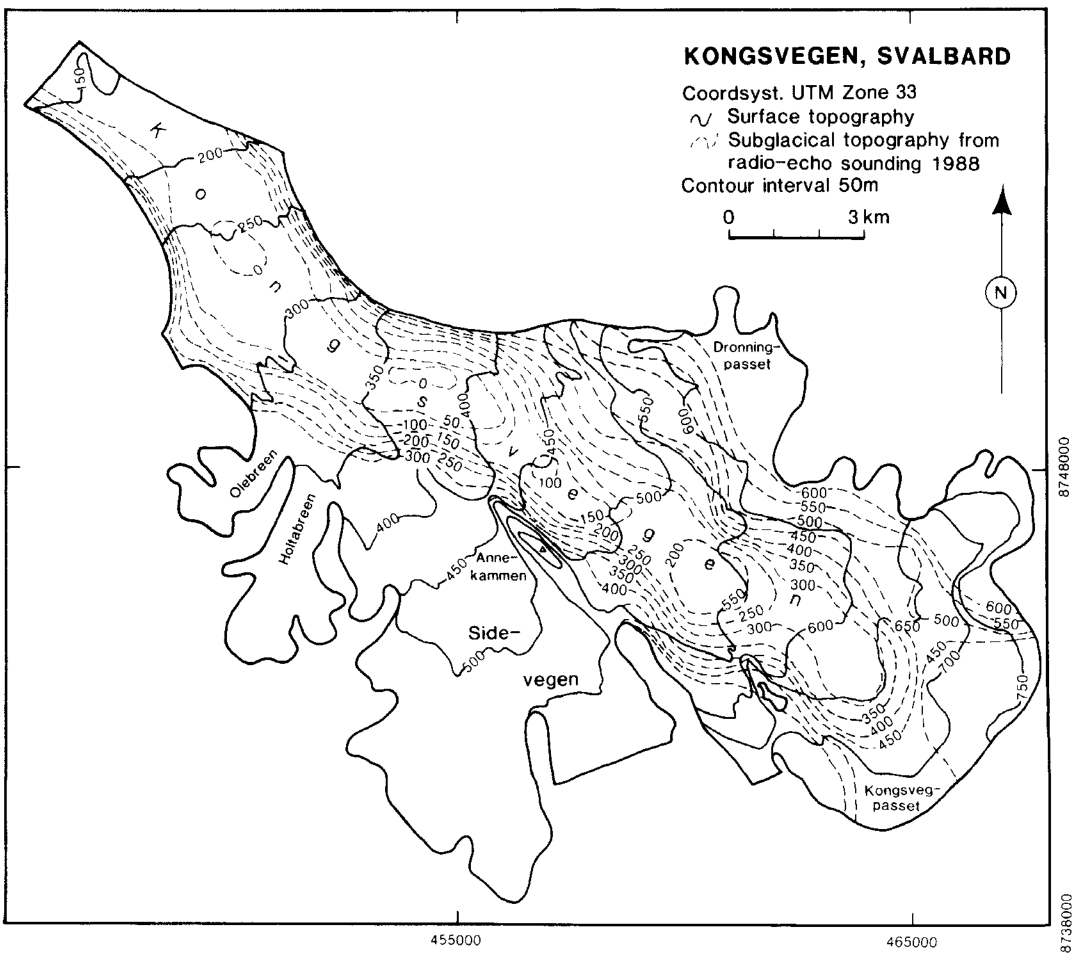

Fig. 8. Surface and subglacial topography for Kongsvegen.

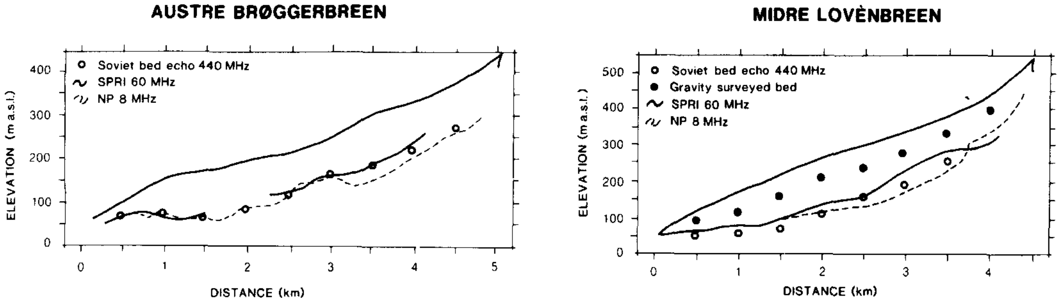

Fig. 9. Comparisons with former radio-echo soundings of longitudinal profiles on Brøggerbreen and Lovénbreen plotted in the diagram from Dowdeswell et al. (1984a). There is good agreement among the three different radio-echo systems.

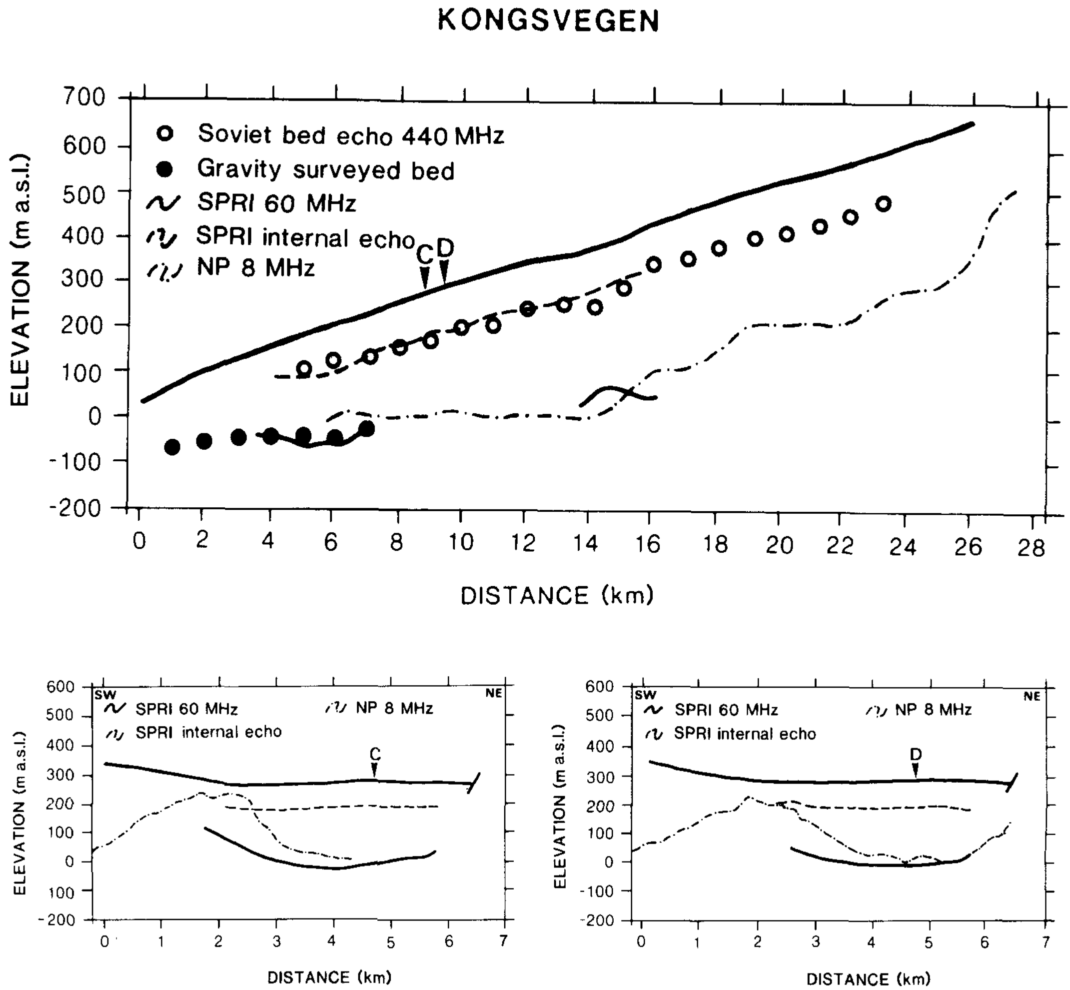

Fig. 10. Longitudinal and cross profiles on Kongsvegen plotted in the diagrams from Dowdeswell et al. (1984a). The 8 MHz radar unit received bed echoes from all parts of the glacier. The longitudinal profile follows the center line, the cross profile D follows the line P13–P14, and profile C follows P15–P16 in Fig. 7.

The most striking difference is the less pronounced depression on this map in the accumulation area of the eastern branch of the glacier. Otherwise the thickness data corresponds quite well.

Comparison with hot water drilling

The ice thicknesses from radio-echo soundings have been compared with ice thicknesses measured in holes drilled with a hot water jet drilling system on Brøggerbreen and Lovénbreen (Table 1). Two holes have been drilled on each of the two glaciers, one in the upper parts and one in the lower parts. The bore-holes are named as follows: on Lovénbreen lower part L3 (at S3) and upper part L9 (at S9); on Brøggerbreen lower part B5 (at S5) and upper part B11 (at S11). The difference in ice depth between the radio-echo soundings and the bore-holes is negligible on Brøggerbreen but greater than the accuracy of the radar (±10 m) on Lovénbreen. The reason for this could be that bore-hole L3 is not exactly vertical and that bore-hole L9 has not penetrated the glacier completely.

On Fridtjovbreen the Soviet drilling on the ice divide reached 211 m which corresponded well with the 60 MHz soundings recorded by Dowdeswell et al. (1984a). Soviet radio-echo soundings also agreed well with the ice divide drilling.

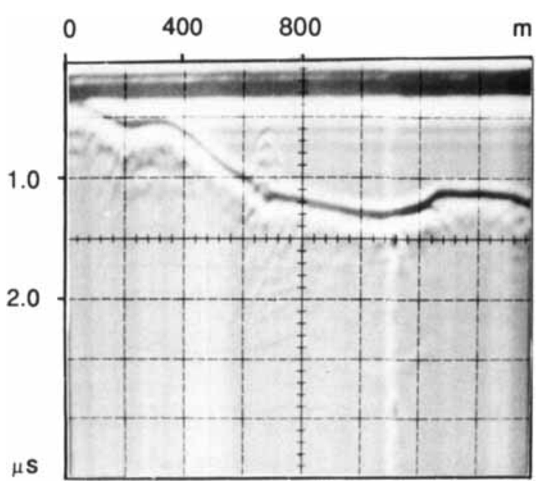

Fig. 11. An internal reflection at approximately 700 m along the profile, probably from an englacial channel, close to S3 on Brøggerbreen.

In the Alps, on Grubengletscher, Haeberli & Fisch (1984) found that depth measurements by a 2.5 MHz radar unit were within ± 5% of 15 bore-hole measurements and that the radar soundings usually underestimated the thickness slightly.

Internal reflections

The observed internal reflections give no evidence of distinct layering of the glacier in zones of temperate ice, but many internal reflections could be observed.

On Brøggerbreen very few internal reflections were observed with the exception of some very clear reflections at two locations, near S3 and S9 (see Fig. 3). The reflections near S3, illustrated in Fig. 11, could be observed on four different profiles. An englacial channel was later in the summer observed leading from a moulin at 60 m depth towards the main river outlet from Brøggerbreen (B. Lefauconnier, pers. comm.). Both the depth and the location correspond with the radio-echo reflections. Similar reflections, but much weaker, were observed on three profiles near S9; these are probably caused by a similar englacial channel. Brøggerbreen has the fewest internal reflections among the three glaciers that have been sounded, and it is also believed to be the coldest of these glaciers.

Two kinds of internal reflections were observed on Lovénbreen, a strong upper reflection and a less strong lower reflection. The upper reflections were similar to those observed on Brøggerbreen and were probably caused by a few distinct water cavities within cold ice, while the lower reflections were probably caused by more numerous water pockets within temperate ice. The depth of this level corresponds with the zero degree level close to 100 m found from temperature measurements in a bore-hole at S9 (see Fig. 5) (Hagen, in prep.) The accumulation area contains more and stronger internal reflections than the ablation area. Such internal reflections are visible on most of the echograms indicating that the glacier is partly temperate with cold ice down to a depth of less than 100 m and temperate ice below. However, we are not able to give any quantitative assessment of the power reflection coefficient from our data. Similar reflections have been studied in a quantitative manner by Bamber (1987b, 1988). The weak lower reflections level appear on our records as a number of individual overlapping hyperbolas exactly in the same way as those Bamber (1988) refers to from Soviet studies.

Internal reflections are more common on Kongsvegen than on the other two glaciers. Strong reflections over the entire glacier were observed, and in some profiles from the accumulation area reflections were seen from the bottom to the surface of the glacier. This could indicate that this glacier has a greater temperate area than the other glaciers. However, it is difficult to see any upper level of these internal reflections which corresponds to those observed by the Soviet (UHF) and SPRI (VHF) equipment.

The same type of reflection hyperbolas observed from the englacial channel at Brøggerbreen were also visible on echoes from Kongsvegen.

Conclusions

The 8 MHz radar-equipment gives good bottom returns for glacier thickness measurements even in the accumulation areas of the glaciers investigated here. There has been no lack of echo from anywhere in the bed, while the British 60 MHz equipment and the Soviet 440 and 620 MHz equipment used in former aerial investigations seldom received bed echoes from the accumulation areas. The soundings were successful also on Kongsvegen where the bed had not previously been seen. The echoes showed that the Kongsvegen bed was at sea level as far as 12 km upstream from the front.

Maps of the subglacial topography have been generated from the radio-echo profiles using an interpolation program for all three glaciers.

Two kinds of internal reflection patterns could be observed. One of them is probably caused by cavities or water channels surrounded by otherwise cold ice. One of these reflections could be related to direct observations of an interglacial drainage channel.

The other kind of internal reflection pattern occurs closer to the bed and usually consists of many reflection hyperbolas with an undefined upper level. We believe that these reflections are caused by a generally higher water content, which indicates temperate ice. It would probably be easier to see the boundary between cold and temperate ice with higher frequency equipment such as the Soviet and British equipment. The most ideal radar unit would probably be a combination, one with which frequency could be changed simply by changing the antenna.

The upper level of these internal reflections was close to 100 m on Lovénbreen. Internal reflections occurred most frequently on Kongsvegen, obviously due to the fact that Kongsvegen is thicker and has a greater accumulation area. Kongsvegen thus has larger parts with temperate ice than the two other investigated glaciers.

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