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Abstract

During spring 1980 740 track kilometres of airborne radio echo sounding were flown in Spitsbergen. SPRI Mk. IV 60 MHz equipment, with a system performance of 140 dB, was used. Navigation was by visual sightings on known points.

Unambiguous bed echoes were recorded for 360 km or 50% of glacier sounding. Maximum recorded ice thickness was 530 m. Bottom echoes were discontinuous or absent in accumulation areas and where the ice surface was heavily crevassed. In southern Spitsbergen bed echoes were recorded over 161 km or 64% of track flown. In Olav V Land 87 km or 60% of track yielded bed returns. In Nordenskiöld Land and north-western Spitsbergen track with bottom returns represented 56 km or 70% and 55 km or 21% of flying, respectively. The relatively low percentage of bed echoes from north-western Spitsbergen was due to a lack of returns from the accumulation areas of Isachsenfonna and Holtedahlfonna.

SPRI Mk. IV results agree well with independent borehole drilling and gravity surveys of ice thickness. However, on certain glaciers 60 MHz data show discrepancies with Soviet echo sounding at 440 and 620 MHz. This is due to Soviet misidentification of an internal echo at the glacier bed. Lack of agreement between SPRI Mk. IV and Soviet 620 MHz equipment may be explained by increased absorption at the higher radio frequency of the Soviet system, and sounding when much meltwater was present.

Many Spitsbergen glaciers are of 'sub-polar' thermal regime. Such ice is less homogeneous and more dielectrically 'lossy' to electromagnetic energy than colder Antarctic ice. In glacier accumulation areas both SPRI Mk. IV and Soviet equipment recorded few bottom returns, probably resulting from the masking of bed echoes by scattering.

Internal reflections were also observed on both 60 MHz and Soviet records, often at between 90 and 110 m below the glacier surface. These may be related to changes in glacier water content according to results from Soviet deep drilling.

Introduction

Glacier ice covers some 60% of the land area of Svalbard. Ice masses ranging in scale from small cirque glaciers to relatively large ice caps are present on Spitsbergen, the largest island in the archipelago. Further, many Spitsbergen glaciers undergo surge cycles. At any time a number are advancing rapidly (Liestøl 1969 and in press; Schytt 1969), whereas many others are slowly retreating. While several ice masses on the island have been investigated in some detail (e.g. Austre Brøggerbreen, Finsterwalderbreen), little basic glaciological information is available for the vast majority of glaciers. Airborne radio echo sounding during the spring of 1980 aimed to provide new glaciological data on about 40 Spitsbergen glaciers of varying size and dynamic regime.

The study was a joint project involving the Scott Polar Research Institute (SPRI), Cambridge, and Norsk Polarinstitutt (NP), Oslo (Drewry et al. 1980). It had three main aims: (1) To test the performance of SPRI Mk. IV 60 MHz radio echo sounding equipment, originally designed for sounding thick polar ice, on 'sub-polar' glaciers in Spitsbergen. This was necessary as a preliminary to more detailed echo sounding of the ice caps of Nordaustlandet, eastern Svalbard, undertaken in 1983. (2) To gain information on the thickness of a wide range of Spitsbergen glaciers. Data from the 1980 airborne survey are already being used in glaciological modelling studies using finite elements. (3) To compare SPRI-NP measurements of the thickness of Spitsbergen glaciers with available evidence from radio echo sounding at higher frequencies (e.g. Macheret 1981; Macheret & Zhuravlev 1982), bore hole data (e.g. Zagorodnov & Zotikov 1981), and gravity surveys (Husebye et al. 1965; Oelsner 1966). Comparison of radio echo sounding data obtained using 60, 440 and 620 MHz systems should yield information concerning the problems of absorption and scattering in glaciers near their melting point.

The paper discusses the radio echo sounding equipment and methods of data reduction used in 1980, and the results of that field season. Comparison is made with existing ice thickness measurements on Spitsbergen glaciers. A number of problems concerning the effectiveness of radio echo sounding on sub-polar glaciers are considered.

Study area

Airborne radio echo sounding of glaciers took place in Spitsbergen during late April and early May 1980. The flight tracks are shown in Figure 1. Flying concentrated in four main areas: Southern Spitsbergen, Olav V Land, Nordenskiöld Land, and North-Western Spitsbergen.

Missions were carried out from Longyearbyen airport, with refuelling at Ny-Ålesund and Hornsund, which allowed maximum use of the helicopter. Flights to and from the glaciers to be sounded were flown at an altitude of c. 1,200 m and a speed of c. 90 kts (165 km hr^{-1}). Over the glaciers flying height was 300–350 m above the ice surface and speed was 60 kts (110 km hr^{-1}). Minimum flying altitude was determined by the recovery time of the echo sounding receiver, in order to record the ice surface return. On 10 missions 38 glaciers were sounded during 20.5 hours of flying (Drewry et al. 1980).

Radio echo sounding equipment and navigation

SPRI Mk. IV 60 MHz equipment

A SPRI Mk. IV pulse-modulated radar system, operating at a centre frequency of 60 MHz, was used during the 1980 field season. This equipment is a modified version of the 35 MHz SPRI Mk. II apparatus described by Evans & Smith (1969). The range accuracy of the SPRI Mk. IV was approximately 10 m or 1.5% of the measured depth, whichever is the greater (Drewry et al. 1980). A short pulse length of 300 ns and receiver bandwidth of 15 MHz were used. System performance, the ratio of peak

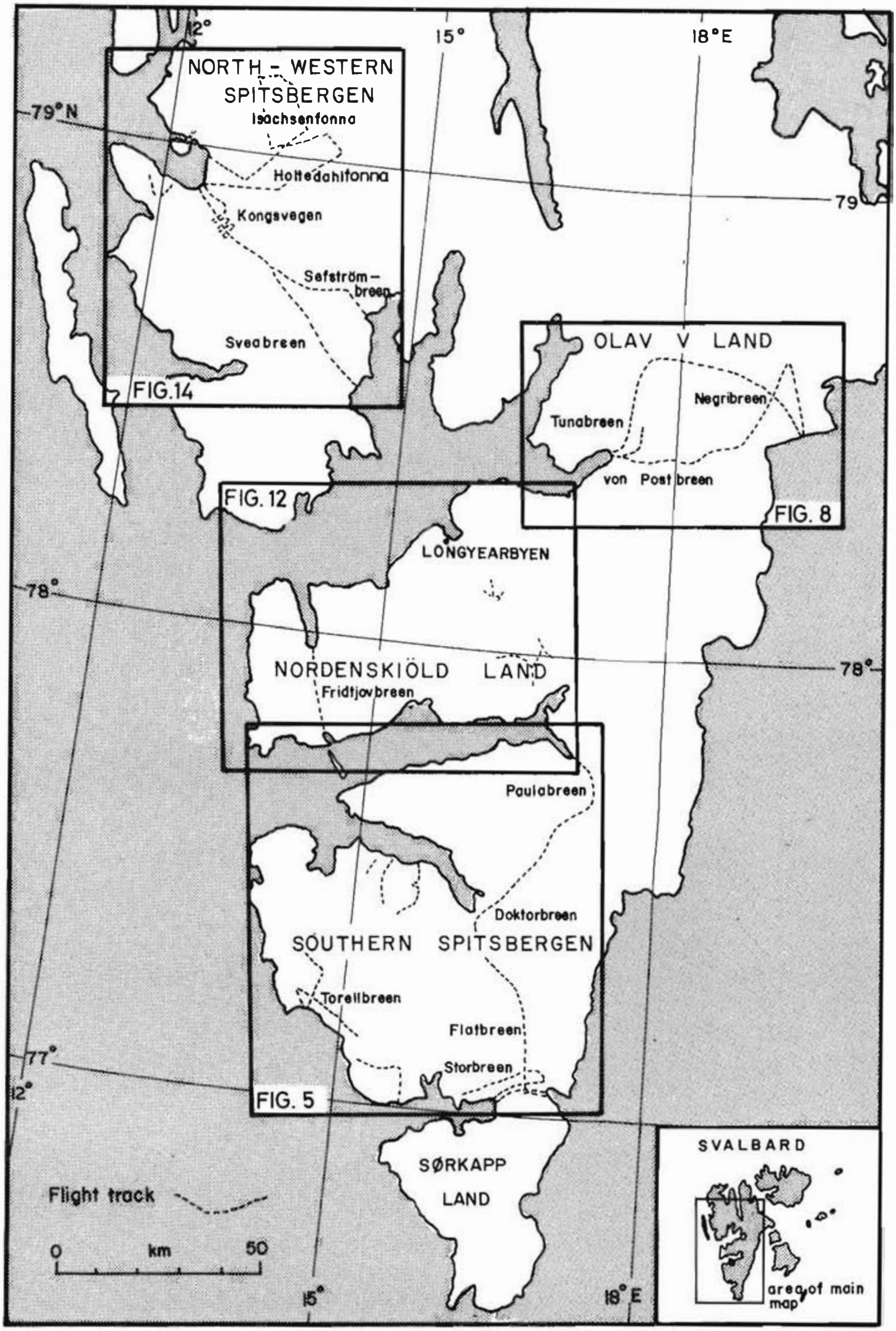


Fig. 1. – Track flown (pecked lines) during radio echo sounding of Spitsbergen glaciers in 1980. Sounding was concentrated in the four areas outlined in the figure: southern Spitsbergen (Fig. 5), Olav V Land (Fig. 8), Nordenskiöld Land (Fig. 12), and north-western Spitsbergen (Fig. 14). The inset shows the position of Spitsbergen within the Svalbard archipelago.

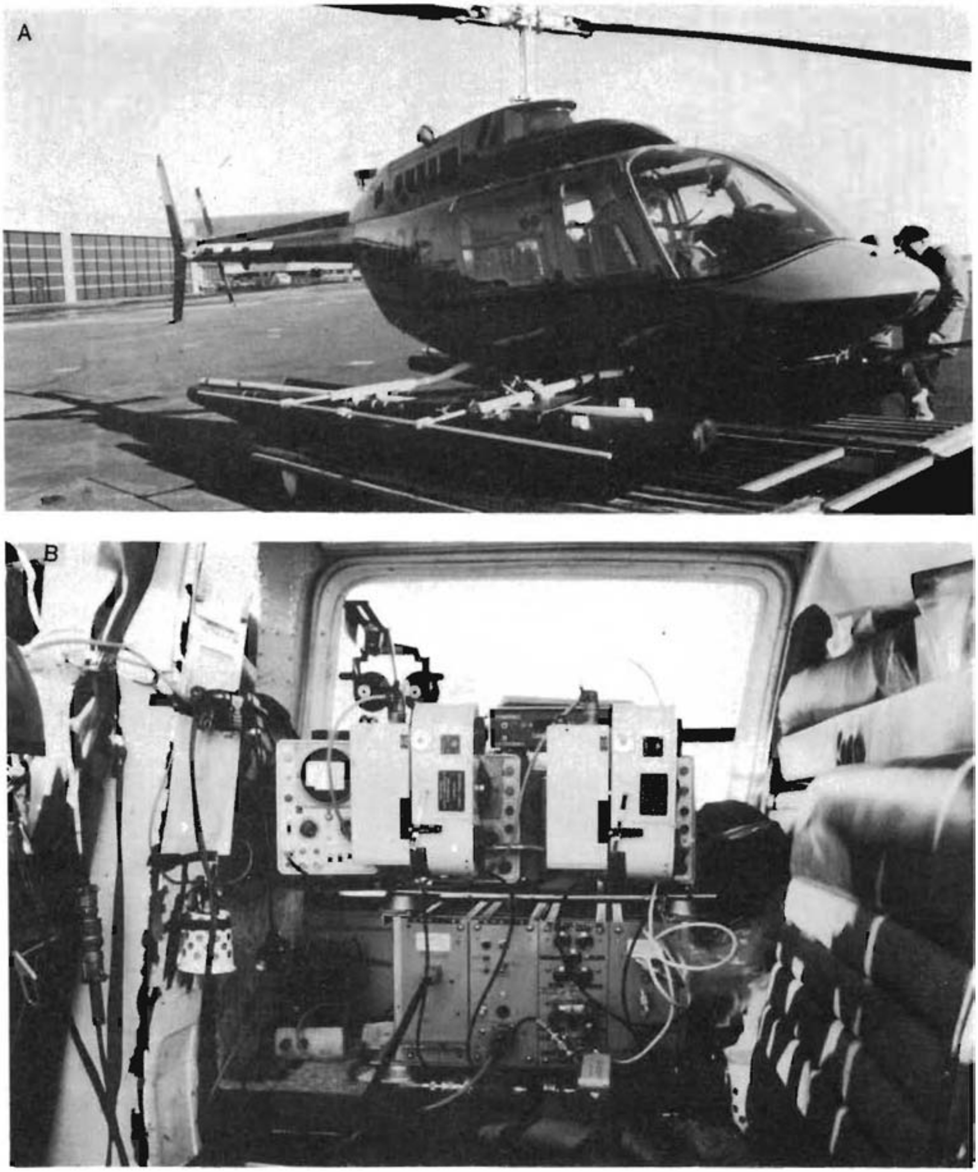


Fig. 2 – A. Simple dipole antenna mounted on the starboard float of a Bell 206 Jetranger helicopter. B. SPRI Mk. IV 60 MHz radio echo sounding equipment mounted in the rear compartment of the helicopter.

power output to receiver input noise, was 160 dB. However, the equipment was normally flown with a 20 dB attenuator to reduce problems of receiver saturation at the low altitudes flown. Antenna gain and the effects of film integration were not included in the value given for system performance. Table 5 lists the parameters of the SPRI Mk. IV 60 radar equipment used during 1980.

The antenna was a simple dipole mounted externally on and parallel to the starboard helicopter float (Fig. 2a). This configuration was sub-optimal because across-track beamwidth was wider than with a conventional mounting orthogonal to

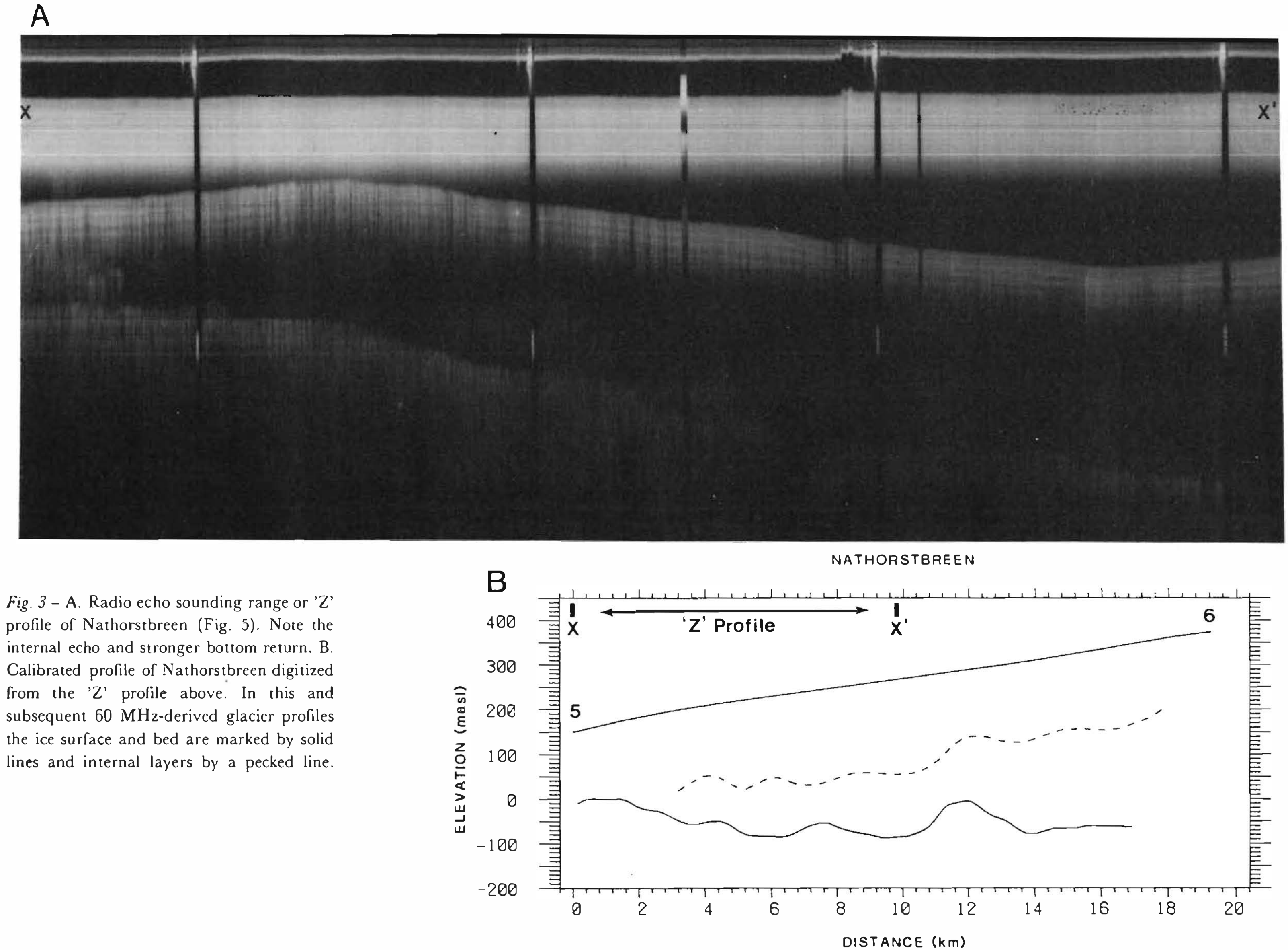


Fig. 3 – A. Radio echo sounding range or 'Z' profile of Nathorstbreen (Fig. 5). Note the internal echo and stronger bottom return. B. Calibrated profile of Nathorstbreen digitized from the 'Z' profile above. In this and subsequent 60 MHz-derived glacier profiles the ice surface and bed are marked by solid lines and internal layers by a pecked line.

flight direction. This might cause increased interference from valley walls. However, an examination of the 'Z' profiles showed that side echoes were not common, and where they occurred they were distinguished easily from the bottom echo. Antenna half-power beamwidth was 100° and forward gain was approximately 2 dB (Table 5).

The Mark IV sounder was mounted in the rear compartment of a Bell-206 Jetranger helicopter (Fig. 2b), and comprised one 60 MHz unit, two recording and one monitoring oscilloscopes. Results were recorded as conventional range or 'Z' profiles on 35 mm film, displaying echo time delay on the y-axis and time on the x-axis (Fig. 3). Calibration of the 'Z' profile by automatic annotation was at minute intervals. Calibration marks, comprising a set of pips 5 μs apart, were placed on the record every minute. A film transport speed of 60 mm minute^{-1} was chosen, which gave a ratio of horizontal to vertical scales on the 35 mm film of approximately 2:1. No other echo sounding data (e.g. 'A' scope records, displaying received power against echo time delay, or echo strength measurement) were recorded during 1980.

Navigation

In this preliminary field season navigation was by visual sightings onto known points (usually mountain summits, ridges and nunataks). On certain glaciers (e.g. Austre Brøggerbreen, Finsterwalderbreen) surveyed markers on the ice surface were overflown. Across-track deviations from the centre-line of valley glaciers are likely to be less than 0.5 km, but could be considerably larger on the nunatak-free areas of Isachsenfonna, Holtedahlfonna and Negribreen (Fig. 1). Variations in helicopter speed along the line of flight were always less than 10% of mean velocity. With a maximum distance of approximately 10 km between known points on valley glaciers, along-track fixing will therefore be about 1 km in error at worst, and considerably better for small glaciers with more numerous reference points. Errors may again be greater on the three nunatak-free areas sounded.

Data reduction

Digitization of the 'Z' record

After developing and printing 'Z' profiles recorded on 35 mm film the terrain clearance, ice surface, bed echo and any internal reflecting horizons were digitized as echo time delays. Digitization took place at approximately 50 m intervals for glaciers less than 10 km long, and every 100 m on larger ice masses. Range errors due to digitization were calculated by repeated digitization of 10 points on the bed of Nathorstbreen, and had standard deviations of between 2.5 and 4.7 m, or less than 3% of ice thickness. Small random digitizing errors were removed from surface and bed profiles by averaging over a window of 5 data points. The internal consistency of ice depth measurements and navigation can be tested by a comparison of points at which flight tracks cross. On Vestre Torellbreen and Kongsvegen, and near the ice divide between Hornbreen and Hambergbreen, ice thickness at crossing-points varied by 4–10 m or between 2 and 4% of total depth. This is a value similar to the range resolution of the Mk. IV system. However, these relatively small differences in ice thickness are in part a function of bed roughness, and may include a large navigational error component if the terrain in the vicinity of crossing-points is smooth (Smith 1972).

em Velocity in ice

Ice thickness was calculated from echo delay time between ice surface and bed. However, the velocity of radio waves in ice is dependent on relative permittivity (ε'). Evans (1965) and Robin et al. (1969) reviewed available data and concluded that within the frequency range 10–10^5 MHz, ε' = 3.17 ± 0.07, giving a velocity in ice of 169 ±2 m μs^{-1}. Johari & Charette (1975) conducted laboratory studies of ice permittivity at 60 MHz, the frequency used during 1980. They noted a slight decrease in permittivity with temperature, with radio wave velocities in ice of 167.7 m μs^{-1} at −1°C and 168.5 m μs^{-1} at −20°C. Robin (1975) also determined a velocity of 167.7 m μs^{-1} in a bore hole in the ice cap on Devon Island, N.W.T., using an interferometric technique at 440 MHz. A radio wave velocity of 168 m μs^{-1} in ice is used in this study.

Firn density and ice thickness calculations

The precence of dry firn leads to the underestimation of ice thickness. In Antarctic and Greenland radio echo sounding studies a standard correction of 10 m is added to calculated ice thickness to take account of low density firn layers near the ice surface (Robin et al. 1969; Robin et al. 1970). Dry firn contains a significant proportion of air and therefore transmits radio waves at a higher velocity than pure ice. The firn layer in the accumulation area of Spitsbergen glaciers is generally much less thick (e.g. Sverdrup 1935) than in the Antarctic ice sheet, where it may exceed a depth of one hundred metres, densification occurring more rapidly at the higher temperatures found in Spitsbergen. In contrast, the effect of rain or meltwater soaked firn on radio wave velocity may lead to overestimation in thickness calculations (Smith & Evans 1972). A drill core from Lomonosovfonna, Spitsbergen, showed that meltwater soaked only the top 2 m of snow during summer, and scarcely penetrated the previous year's firn (Kotlyakov et al. 1980). Using a value of 2.3:1 (Smith & Evans 1972) for the ratio of radio wave velocity in soaked firn (density 500 kg m^{-3}) to that in ice yields an overestimate of 2.6 m in ice thickness for a 2 m thick soaked firn layer. This is considerably less than the range resolution of the SPRI Mk. IV system. Further, such soaking of the firn layer is unlikely to have occurred during spring-time radio echo sounding of Spitsbergen glaciers. In this paper, no corrections are made for the presence of a firn layer, soaked or otherwise, because these errors are relatively small and variable in space and time.

Bed profile migration or deconvolution

Distortion of the bedrock profile may occur because the radar antenna beamwidth is relatively wide, and the first echo return, which comes from the nearest point on the bed, may not necessarily indicate ice thickness at nadir. Harrison (1970) developed a

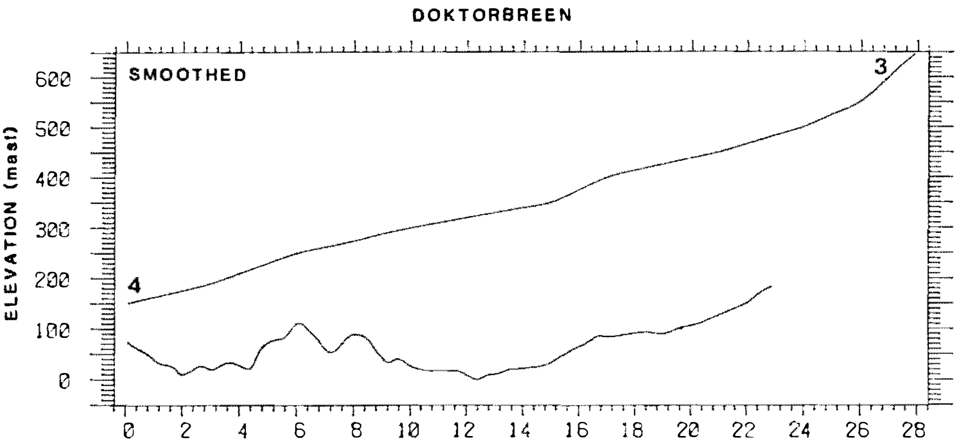


Fig. 4. – Long profile of Doktorbreen, southern Spitsbergen (Fig. 5).

computer procedure known as deconvolution, similar to seismic migration, whereby the 'true' bedrock profile may be reconstructed, although it ignores returns in the transverse direction. However, this problem is only serious where steep slopes are encountered. Beneath the Spitsbergen glaciers studied the steepest sections of unmigrated bed rarely exceed 5° and are generally less than 2°. Deconvolution was, therefore, considered unnecessary, but the bed profile of Doktorbreen (Fig. 4) was, nonetheless, deconvoluted in order to test this. The results showed that at these low slopes (<5°) the corrections introduced by deconvolution are minimal. It should be noted that the glacier profiles presented in subsequent sections are vertically exaggerated by between 5 and 19 times, and therefore bed slopes appear greater than they in fact are.

Glacier surface elevations

In constructing glacier profiles (e.g. Fig. 4) surface elevations were obtained from existing maps of Spitsbergen produced by Norsk Polarinstitutt. The major data source was the 1:100,000 map series, with a contour interval of 50 m. These maps were constructed from air photographs, in some areas dating back to 1936. 1:20,000 maps with a contour interval of 10 m, published in 1970 and 1979, were available for Finsterwalderbreen, Austre Brøggerbreen and Midre Lovénbreen. The procedure involved fitting 1980 ice thickness data to surface elevations using navigational information. However, glacier surface elevations may have changed considerably since map production. The profiles of Von Postbreen and Hessbreen have been modified substantially as a result of rapid advances and thickening at the snout (Liestøl 1969, 1976a; Schytt 1969). For other glaciers surface elevations are generally accurate to approximately 10–20 m in their upper and central areas, whereas the lower reaches may have thinned by up to 100 m vertically, particularly in the case of data taken from the oldest maps. Most glacier front positions are based on observations made during the 1970s from air reconnaissance, air photographs and Landsat satellite imagery.

Results of airborne radio echo sounding

A total of 740 track-km of airborne radio echo sounding was undertaken during 1980 (Fig. 1). Unambiguous bed echoes were recorded for 360 km or about 50% of this distance. Echoes from internal reflectors were also noted on 'Z' profiles from a number of glaciers (e.g. Fig. 3). The maximum ice thickness sounded by the SPRI Mk. IV system was 530 m on Holtedahlfonna.

Bottom echoes were discontinuous or absent in two main situations: first, in the accumulation area of large glaciers and ice caps, for example Isachsenfonna; second, where the ice surface was heavily crevassed, a phenomenon often associated with glacier surging. Scattering and absorption of electromagnetic waves are problems in these situations (Smith & Evans 1972). Scattering occurs from facets on the broken surface of glaciers and from internal reflectors such as ice lenses. The latter may be present due to the refreezing of meltwater in glacier accumulation areas. Absorption also increases in the accumulation areas of many Spitsbergen glaciers because temperatures below the winter cold wave are often at or near the melting point (e.g. Sverdrup 1935). Water may, therefore, be present both internally and at the glacier surface. The problems of radio echo sounding on sub-polar glaciers and comparison with other published work on the thickness of Spitsbergen glaciers are discussd further below.

The detailed results of radio echo sounding in Spitsbergen are now presented by area. The percentage of track with bottom echoes is reported for each glacier sounded, and the thickness of glacier ice is shown diagrammatically for those ice masses with relatively continuous bed returns.

Southern Spitsbergen

Radio echo sounding flight lines in Southern Spitsbergen are mapped in Figure 5. The total length of glacier sounding was 251 km, and bed echoes were recorded over 161 km or 64% of this distance (Table 1). The deepest ice penetrated in southern Spitsbergen was 410 m on Nathorstbreen (Fig. 3).

The problem of radio echo sounding on surging glaciers is demonstrated by the complete absence of bottom returns from Hessbreen (Fig. 5). This glacier was still very crevassed in 1980 after undergoing rapid advance between 1972 and 1974 (Liestøl 1967a). By contrast, the nearby Finsterwalderbreen has not surged since between 1898 and 1910 (Liestøl 1969), and in 1980 its surface was largely unbroken. Bed echoes were recorded throughout its length. This bedrock profile and ice thickness information is being used as input to a modelling study of the dynamics of Finsterwalderbreen using finite element methods.

Several passes were flown over the ice covered area separating Hornsund and Hambergbukta (Fig. 5) to establish whether or not any bedrock extended above sea level between Sørkapp Land and the main landmass of Spitsbergen to the north. Ice over 200 m thick was present in this area, and bedrock reached up to approximately 25 m above sea level beneath these glaciers (Figs. 6 and 7). However, these estimates of absolute altitude are based on ice surface contours from air photographs obtained in the late 1930s and may therefore contain substantial inaccuracies. Figure 6 nonetheless confirms that no deep trough exists here.

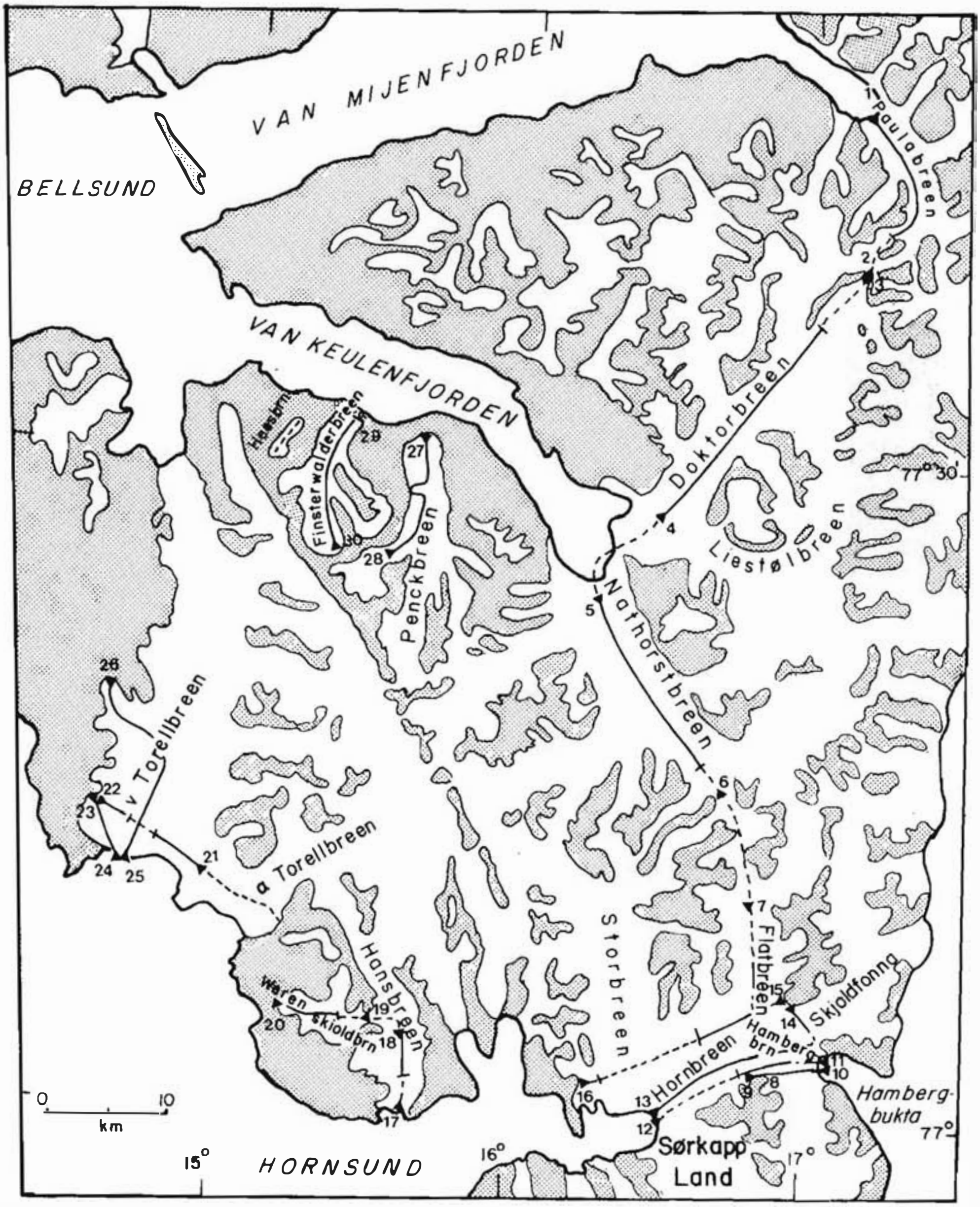


Fig. 5. – Radio echo sounding flight lines in southern Spitsbergen (Fig. 1). Solid lines represent flight track with bed echoes, and pecked lines mark areas where bottom returns were not recorded (Table 1). Numbers refer to glacier long profiles illustrated in succeeding figures.

The long profiles of Nathorstbreen and Doktorbreen are found in Figures 3 and 4, and Paulabreen is illustrated in Figure 7. The results of radio echo sounding on each glacier in this area are summarized in Table 1. Ice thickness diagrams of Finsterwalderbreen, Penckbreen, Hansbreen, Werenskioldbreen and Torellbreen are presented later when comparison is made with previous radio echo sounding results (Figs. 16, 17 and 18).

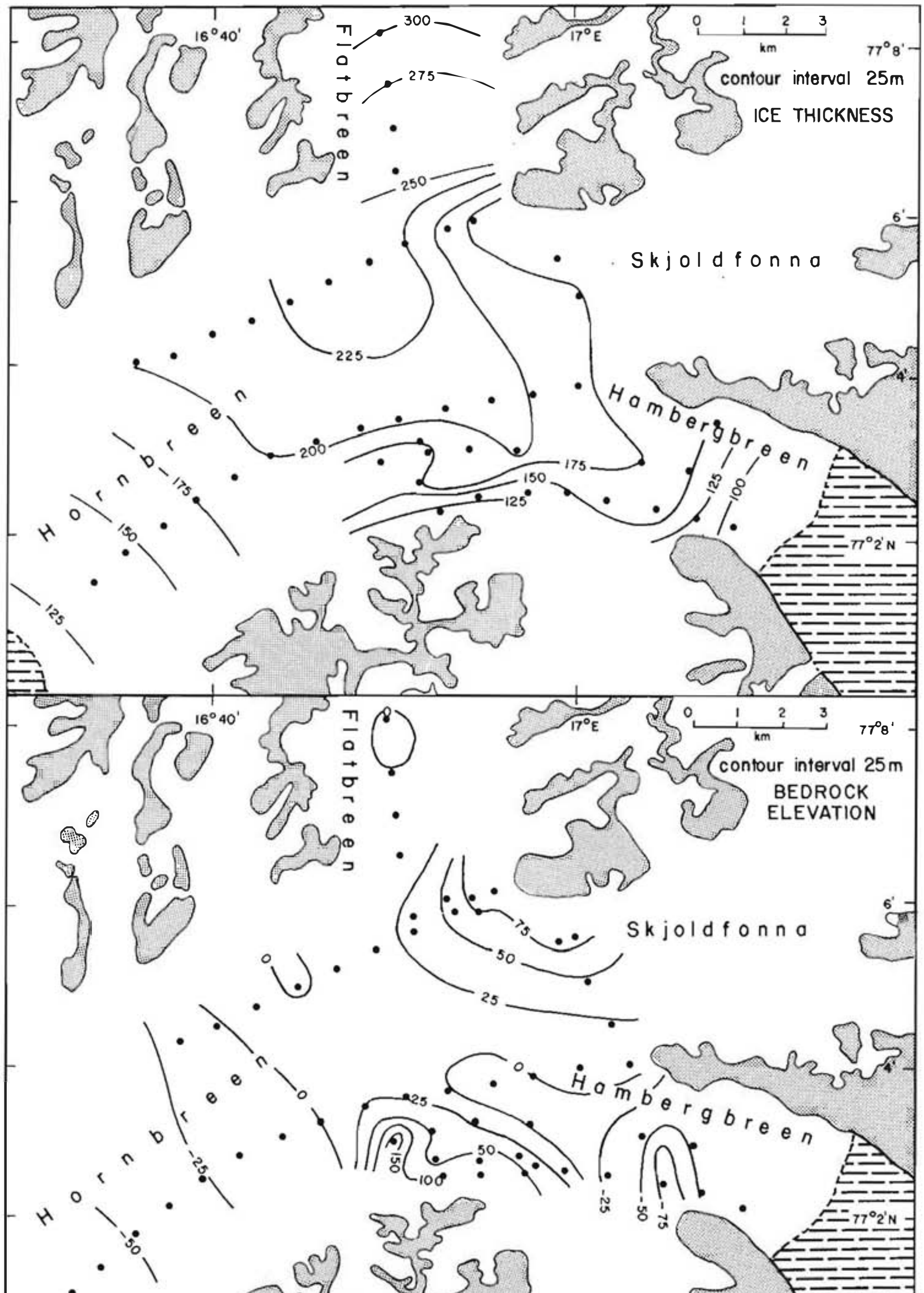


Fig. 6. – The ice covered area separating Sørkapp Land and the main landmass of Spitsbergen to the north: a) ice thickness; b) bed elevations. The data are from airborne radio echo sounding and flight tracks are shown as dots.

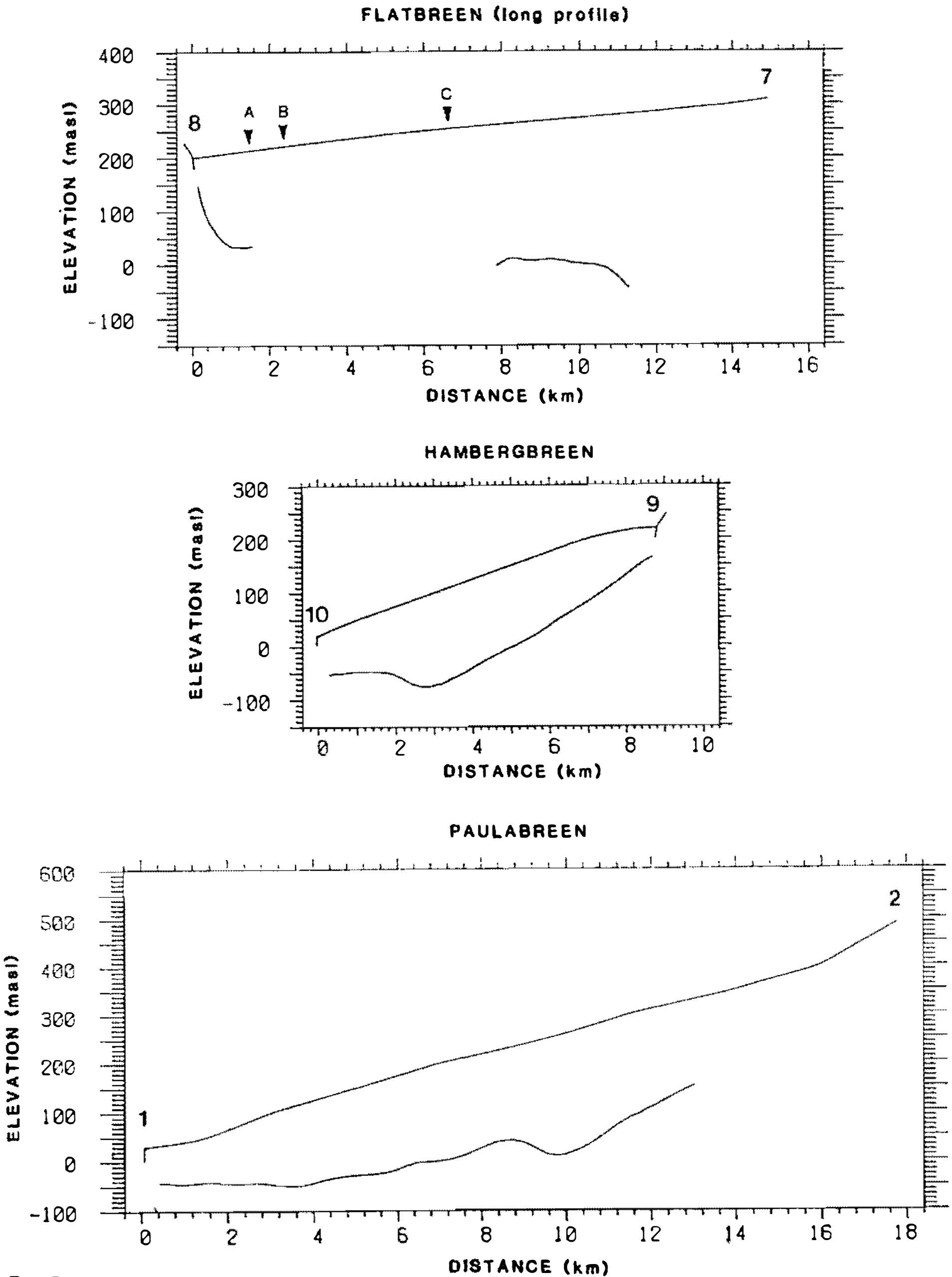


Fig. 7, see next page.

Olav V Land

In Olav V Land 145 km of radio echo sounding was carried out (Fig. 8) and bottom echoes were recorded for 87 km or 60% of this total (Table 2). The thickest ice sounded was 430 m on Negribreen.

Bottom returns were observed on less than 20% on Tunabreen (Table 2), the ice reaching a thickness of over 250 m some 8 km from the snout. This glacier surged in 1970. Bed echoes also disappeared in the accumulation areas of Von Postbreen and

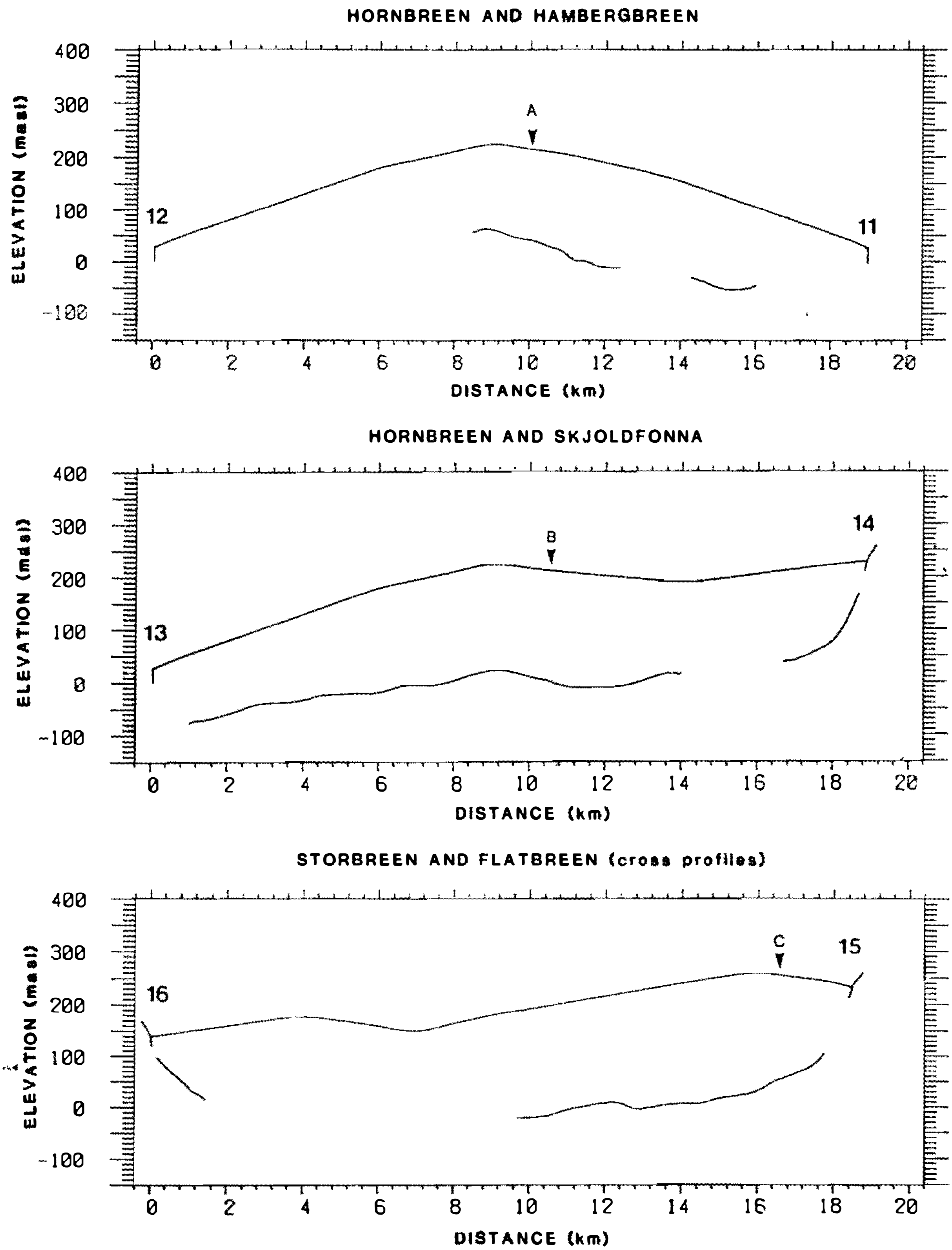


Fig. 7. – Profiles of the southern Spitsbergen glaciers Flatbreen, Hambergbreen, Hornbreen, Skjoldfonna, Storbreen and Paulabreen. Numbers locate the profiles in Figure 5. The letters mark where profiles intersect.

Negribreen. On Bogebreen, which was observed to be surging in 1980 (Fig. 9), the bed was obscured by scattering from its crevassed surface (Fig. 10). Long profiles of the glacier surface and bed for Petermannbreen, Langhansbreen, Hayesbreen and Von Postbreen are shown in Figure 11. The thickness of Negribreen is compared with existing data in Figure 17. There is no evidence that the lower part of Negribreen is afloat.

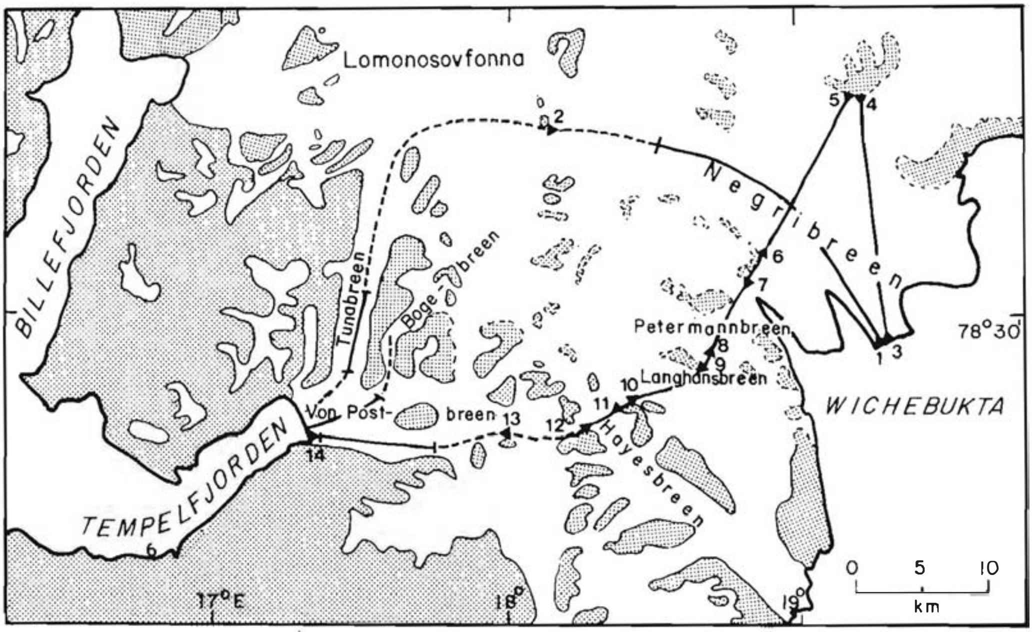


Fig. 8 – Radio echo sounding flight lines in Olav V Land (Fig. 1). Solid lines represent flight track with bed echoes, and pecked lines mark areas where bottom returns were not recorded (Table 2). Numbers refer to glacier profiles illustrated in succeeding figures.

Table 1. Details of airborne radio echo sounding in Southern Spitsbergen.

Glacier	*Total Track* (*km*)	*Track with Bed* (*km*)	(*%*)
Doktorbreen	28.0	23.0	82
Finsterwalderbreen	12.0	12.0	100
Flatbreen	30.0	13.0	43
Hambergbreen	17.0	13.0	76
Hansbreen	14.0	4.0	29
Hessbreen	4.5	0.0	0
Hornbreen	23.0	14.0	61
Liestølbreen	3.0	0.0	0
Nathorstbreen	28.0	17.0	61
Paulabreen	18.0	13.0	72
Penckbreen	13.0	12.5	96
Skjoldfonna	5.0	2.0	40
Storbreen	7.0	1.5	21
Austre Torellbreen	8.0	0.0	0
Vestre Torellbreen	34.0	31.5	93
Werenskioldbreen	7.0	5.0	71
Total	251.5	161.5	64

Note: Glaciers located in Figure 5.

Nordenskiöld Land

Bottoms returns were observed over 56 km or 70% of the 80 track-km flown in Nordenskiöld Land (Table 3; Fig. 12). The maximum ice thickness recorded in this area was 320 m on Fridtjovbreen and Slakbreen (Fig. 13). The glaciers Fridtjovbre-

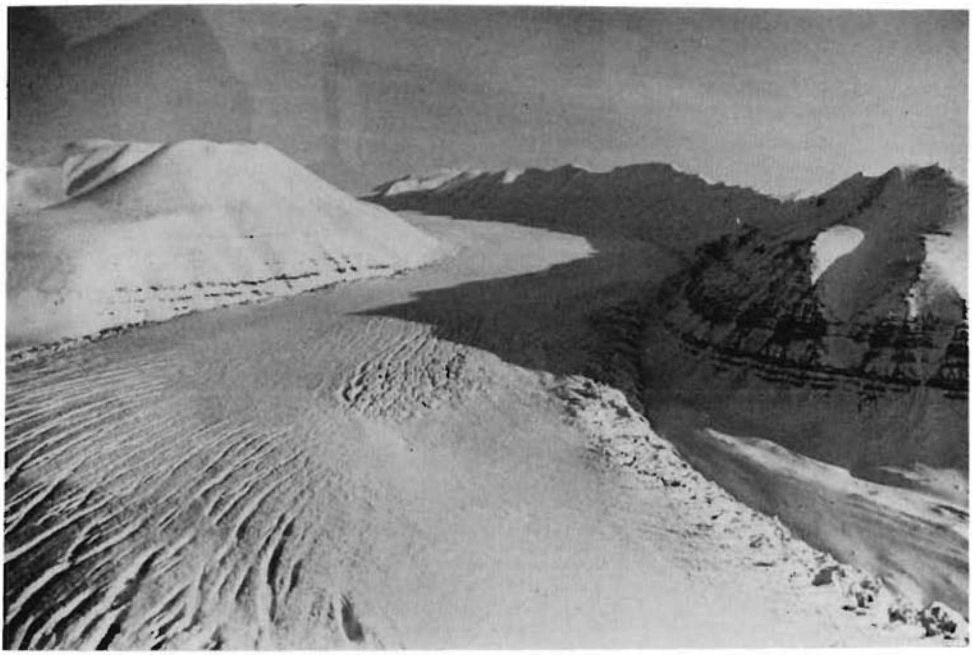


Fig. 9. – Photograph showing the heavily crevassed surface of the surging glacier Bogebreen (Figs. 8 and 10) during rapid advance.

Table 2. Details of airborne radio echo sounding in Olav V Land.

Glacier	*Total Track* (*km*)	*Track with Bed* (*km*)	(*%*)
Bogebreen	5	0	0
Hayesbreen	3	1	34
Langhansbreen	6	6	100
Negribreen	62	52	84
Petermannbreen	7	7	100
Tunabreen	33	6	18
Von Postbreen	29	15	52
Total	145	87	60

Note: Glaciers located in Figure 8.

en, Austre Grønfjordbreen and Slakbreen, the largest outlet glacier of Gruvfonna, provided continuous echoes over their entire length (Table 3).

The small ice caps Foxfonna and Gruvfonna were sounded to provide ice thickness information relevant to mining operations in the underlying Tertiary coal-bearing strata. Such data had been collected previously only for a part of Foxfonna (Liestøl 1974), and allowed the proximity of existing shafts to the glacier bed to be calculated, and plans for future exploitation evaluated.

North-Western Spitsbergen

Whereas radio echo sounding missions in the three areas of Spitsbergen so far discussed all have bottom returns from approximately 50% or more of flight tracks, the 263 km flown over the north-western part of the island records bed echoes over

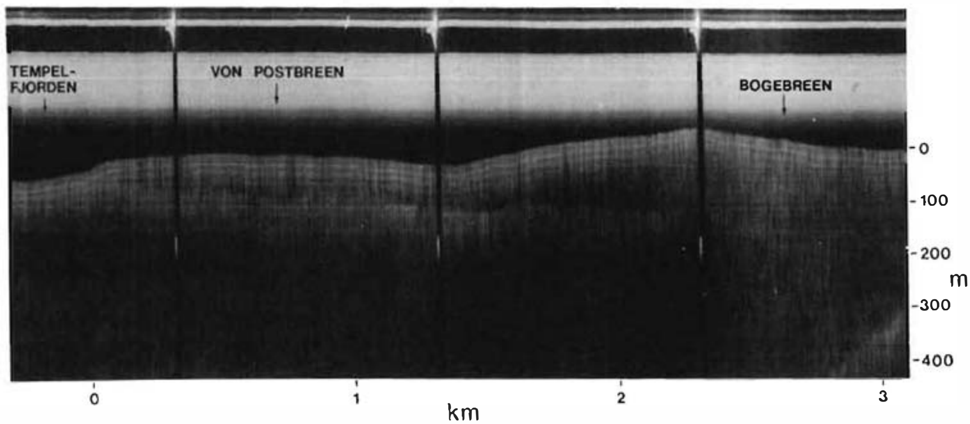
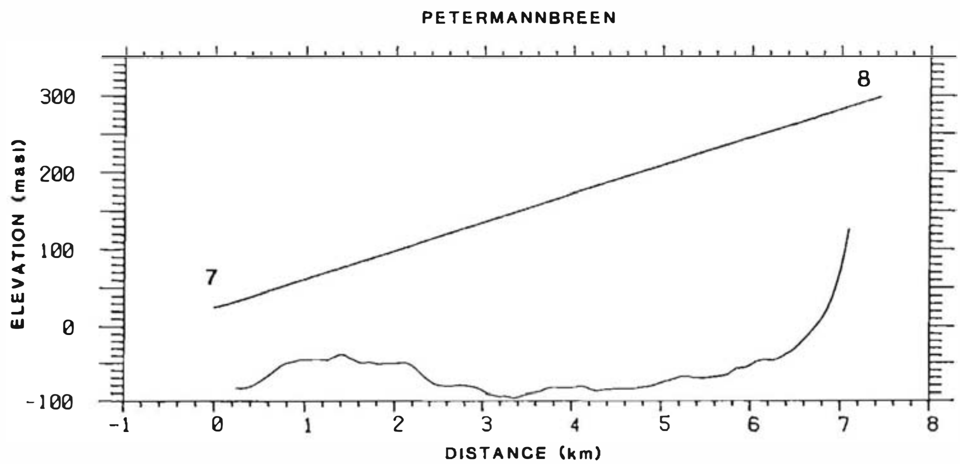


Fig. 10. – Radio echo sounding 'Z' profile of Bogebreen (Fig. 9), showing the masking of bottom returns by scattering from surface crevasses. A bed echo can be seen on Von Postbreen, but on the surging Bogebreen the bottom is obscured.



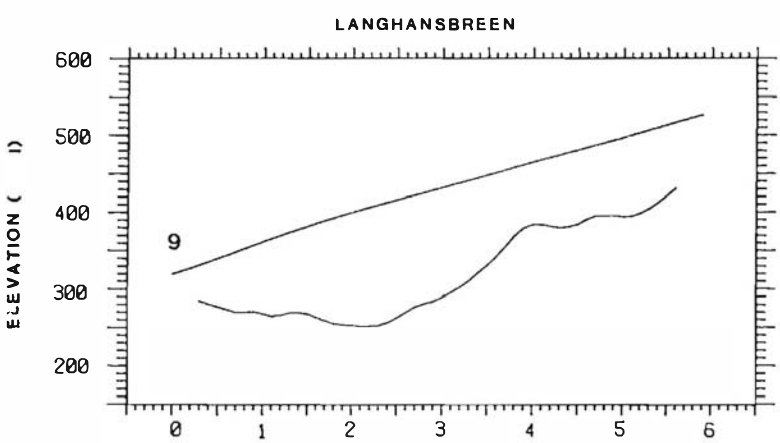


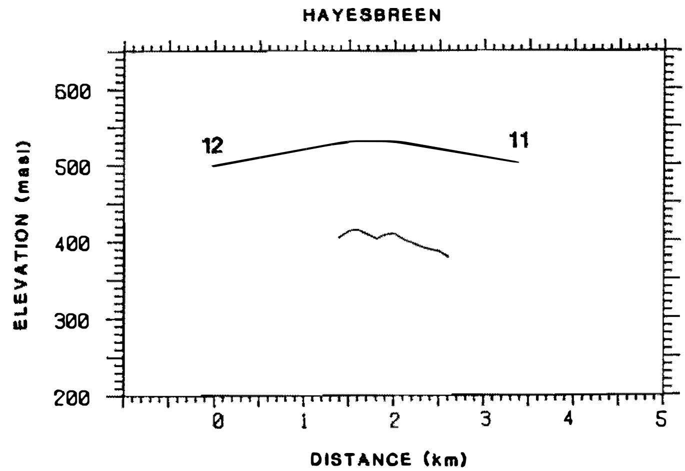
Fig. 11, see next page.

only 55 km or 21% of track (Table 4; Fig. 14). The thickest ice sounded was 530 m on a limited section of Holtedahlfonna.

The small valley glaciers Austre Brøggerbreen and Midre Lovénbreen, together with the larger Kongsvegen, exhibited the most continuous bed echoes in this area, although returns from the base of Kongsvegen disappear in the accumulation area. Ice thickness data for these glaciers are compared with existing measurements below.

On the larger ice fields of Isachsenfonna and Holtedahlfonna bottom echoes were recorded over less than 20% of 125 km of flight track (Table 4; Fig. 14). This may be due to the presence of relatively thick ice at or near its melting point (Sverdrup 1935).

Bottom echoes were recorded for the lower 16 km of Kongsvegen, excluding the heavily crevassed snout (Fig. 15). In addition to this long profile, six cross-profiles of the glacier were obtained (Fig. 15). These data, together with velocity measurements carried out during the 1960s (Voigt 1965; Vivet & Lliboutry 1978), provide the basic information necessary to estimate the mass flux of Kongsvegen.



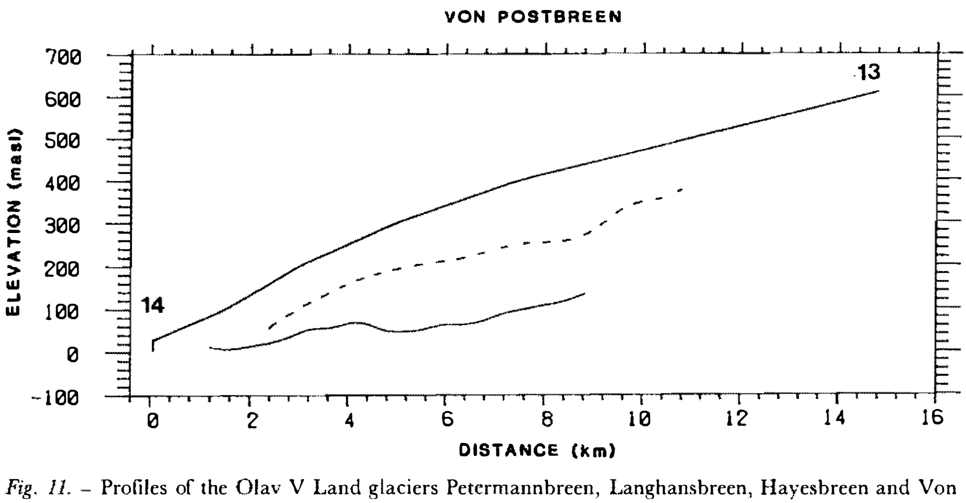


Fig. 11. – Profiles of the Olav V Land glaciers Petermannbreen, Langhansbreen, Hayesbreen and Von Postbreen. Numbers locate the profiles in Figure 8.

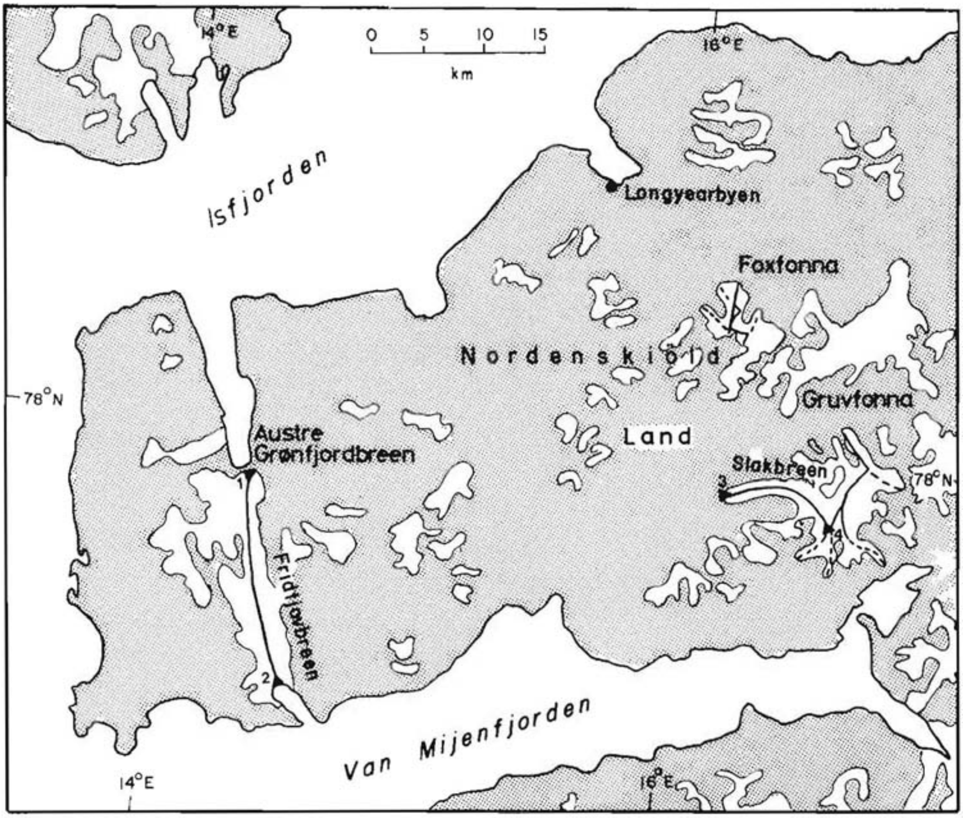


Fig. 12. – Radio echo sounding flight lines in Nordenskiöld Land (Fig. 1). Solid lines mark areas with bed echoes, and pecked lines represent flight track where bottom returns were not recorded (Table 3). Numbers refer to glacier long profiles illustrated in succeeding figures.

Table 3. Details of airborne radio echo sounding in Nordenskiöld Land.

Glacier	*Total Track (km)*	*Track with Bed (km)*	*(%)*
Foxfonna	25.5	11.0	43
Fridtjovbreen	11.0	11.0	100
Austre Grønfjordbreen	7.0	7.0	100
Gruvfonna (excluding Slakbreen)	24.0	15.0	62
Slakbreen	12.0	12.0	100
Total	79.5	56.0	70

Note: Glaciers located in Figure 12.

Radio echo sounding of an ice-filled pass between Kongsvegen and Uvêrsbreen (Figs. 14 and 15) was undertaken to gain further information on a mainly subglacial glacier-dammed lake, Setevatnet (Liestøl 1976b). Results did not show identifiable bottom returns in this area (Fig. 15). Nor was there any sign of the 1 km long crack at the surface of Kongsvegen, some 2 km down-stream from Setevatnet, through which water discharged to drain the lake in 1975.

The lower 3 km of Blomstrandbreen were also sounded during 1980 (Fig. 14). The snout of the glacier connects Blomstrandhalvøya with the mainland to the north. Ice thicknesses of up to 130 m indicate that Blomstrandbreen is grounded below sea level and that Blomstrandhalvøya is therefore an island.

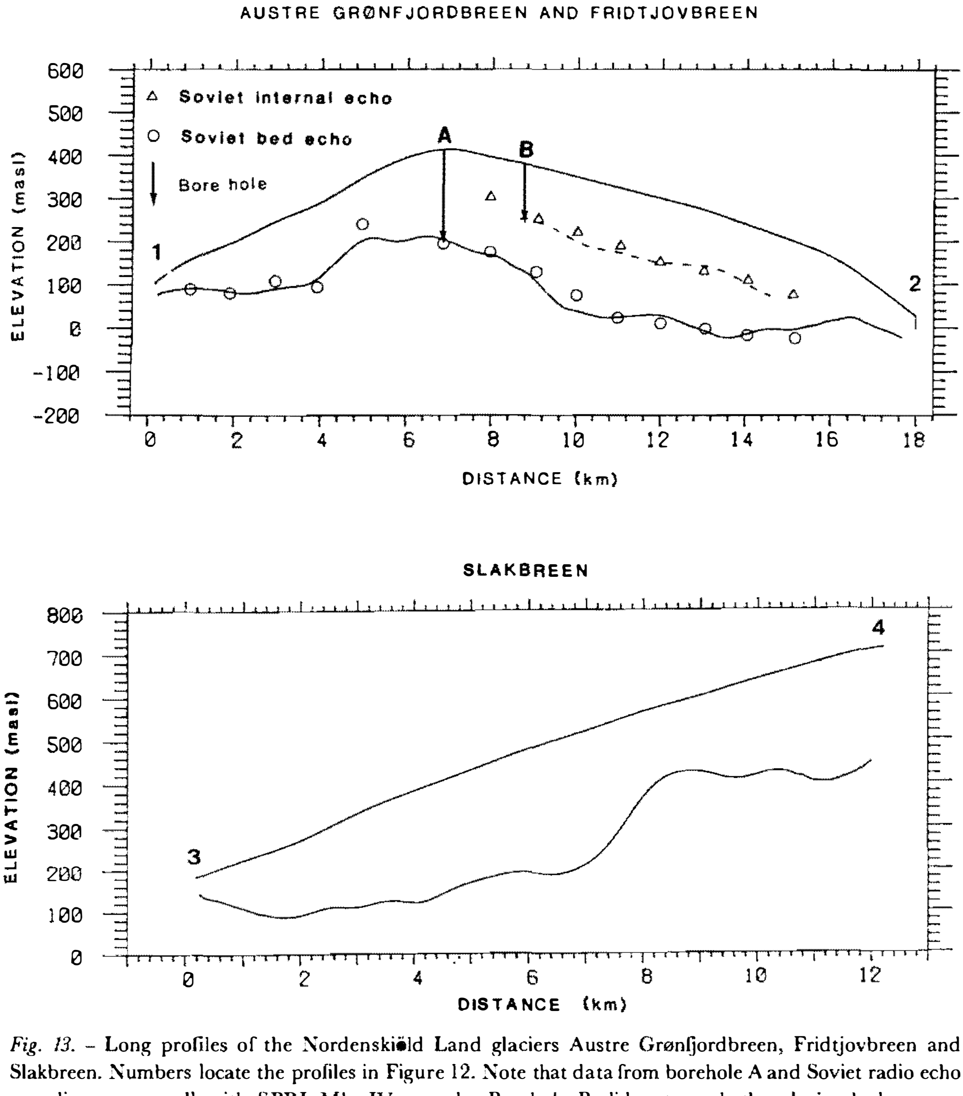


Fig. 13. – Long profiles of the Nordenskiöld Land glaciers Austre Grønfjordbreen, Fridtjovbreen and Slakbreen. Numbers locate the profiles in Figure 12. Note that data from borehole A and Soviet radio echo sounding agree well with SPRI Mk. IV records. Borehole B did not reach the glacier bed.

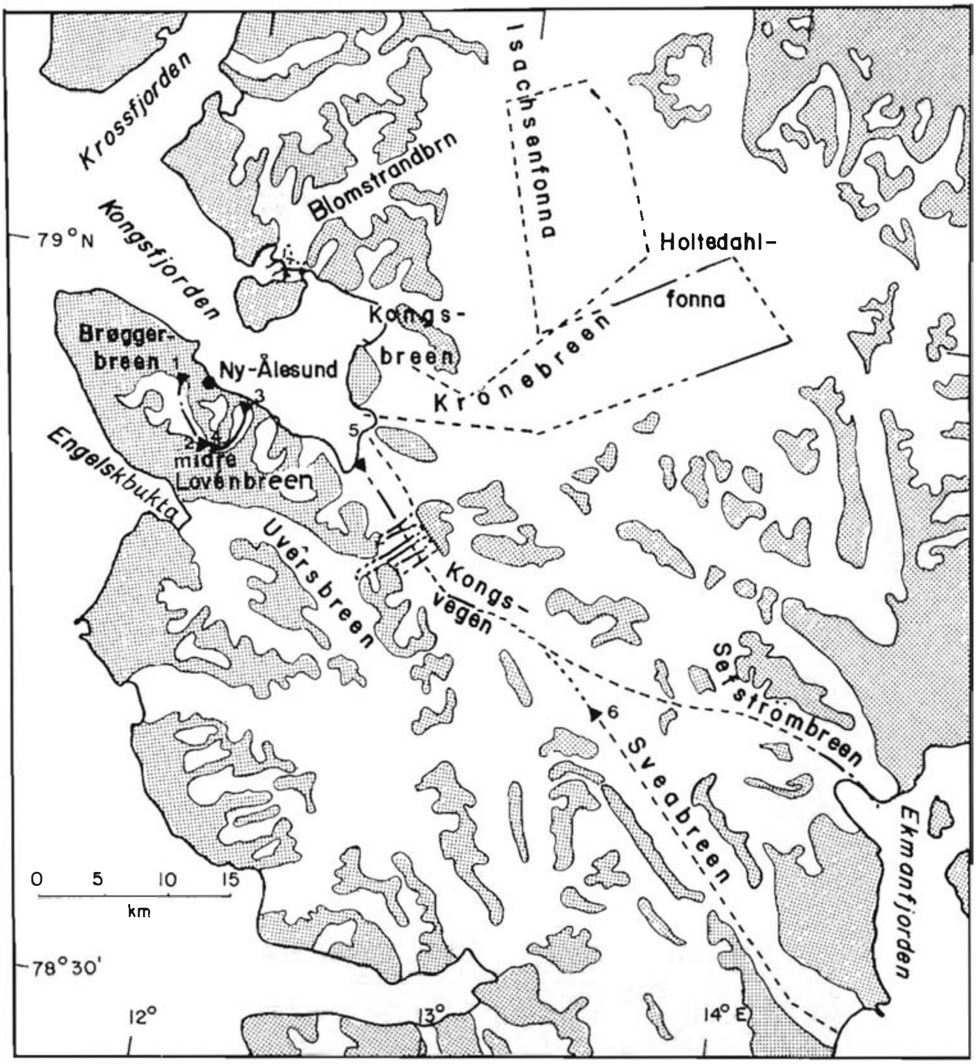


Fig. 14. – Radio echo sounding flight lines in north-western Spitsbergen (Fig. 1). Solid lines represent flight track with bed echoes, and pecked lines mark areas where bottom returns were not recorded (Table 4). Numbers refer to glacier profiles illustrated in succeeding figures.

Table 4. Details of airborne radio echo sounding in North-Western Spitsbergen.

Glacier	*Total Track (km)*	*Track with Bed (km)*	*(%)*
Austre Brøggerbreen	5.0	3.0	60
Blomstrandbreen	5.0	2.0	40
Kongsvegen (long prof.)	27.0	9.0	33
Kongsvegen (cross prof.)	33.5	15.5	46
Kronebreen-Holtedahlfonna-Isachsenfonna-Kongsbreen	125.0	16.0	13
Midre Lovénbreen	4.5	4.2	93
Sefströmbreen	29.5	5.5	19
Sveabreen	34.0	0.0	[illegible]
Total	263.5	55.2	21
Total	138.5	39.2	28
(excluding Kronebreen-Holtedahlfonna-Isachsenfonna-Kongsbreen)			

Note: Glaciers located in Figure 14.

Comparison with existing ice thickness data

Previous estimates of the thickness of Svalbard glaciers have used gravity and seismic methods, boreholes and radio echo sounding. Existing results using each method are compared with data from 60 MHz radar sounding undertaken in 1980.

Gravity surveys

Gravity surveys of ice thickness have been conducted in several areas of Svalbard (Hollin 1956; Husebye et al. 1965; Oelsner 1966), and seismic shooting has taken place in Nordaustlandet (Ekman 1971). In Spitsbergen, gravity surveys are available for Finsterwalderbreen (Husebye et al. 1965), Kongsvegen and Midre Lovénbreen (Oelsner 1966). This latter method yields ice depths averaged over an area with sides approximately equivalent to glacier depth. Ice thicknesses on Finsterwalderbreen and Kongsvegen from gravity surveys and 60 MHz radio echo sounding rarely deviate by more than 25 m or 10% of glacier depth (Fig. 16). This is similar to a comparison of results from these two techniques in Antarctica (Drewry 1975). However, on Midre Lovénbreen (Fig. 16) the depths obtained from Oelsner's (1966) gravity survey are approximately 50% of those for both SPRI Mk. IV and Soviet sounding (Macheret & Zhuravlev 1982).

Borehole measurements

Deep glacier drilling operations in Svalbard have taken place on Foxfonna (Liestøl 1974), on Fridtjovbreen, Lomonosovfonna and Amundsenisen (Zagorodnov & Zotikov 1981), and on Vestfonna in Nordaustlandet (Zagorodnov & Zinger 1982).

Thermal drilling on the ice divide between Austre Grønfjordbreen and Fridtjovbreen (Fig. 13) reached the glacier bed at 211 m (Zagorodnov & Zotikov 1981). A second borehole in this area did not reach the glacier bed. This was the only glacier

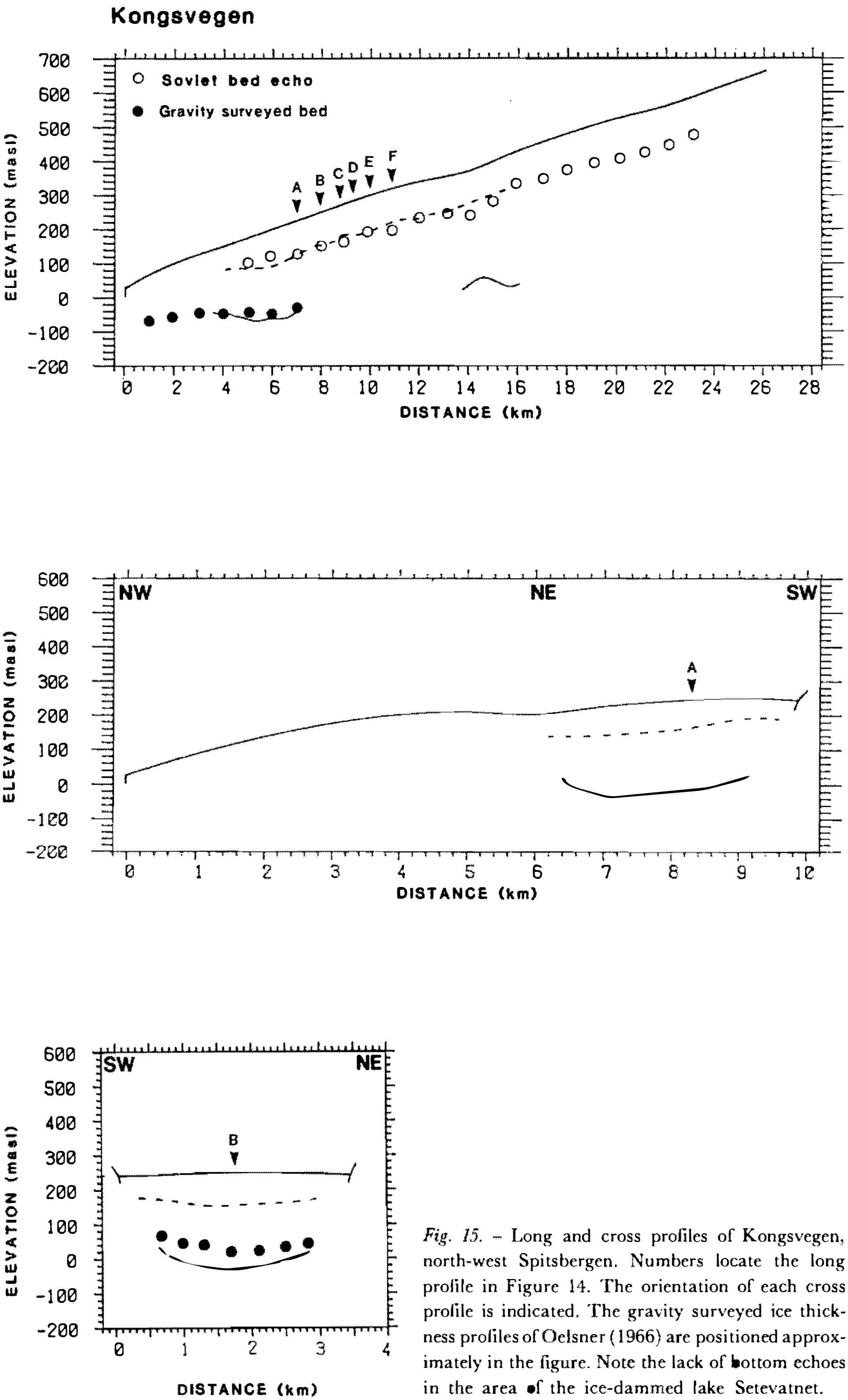
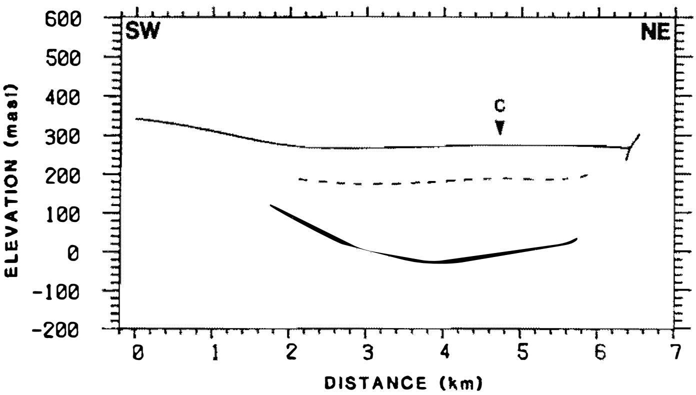


Fig. 15. – Long and cross profiles of Kongsvegen, north-west Spitsbergen. Numbers locate the long profile in Figure 14. The orientation of each cross profile is indicated. The gravity surveyed ice thickness profiles of Oelsner (1966) are positioned approximately in the figure. Note the lack of bottom echoes in the area of the ice-dammed lake Setevatnet. →



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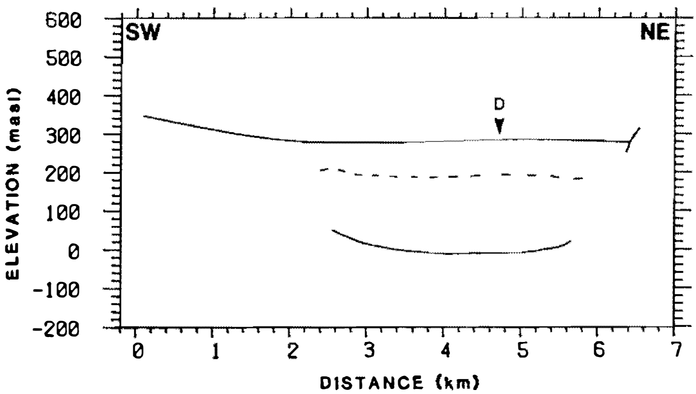

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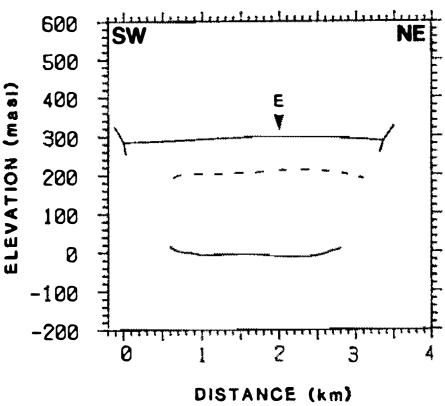

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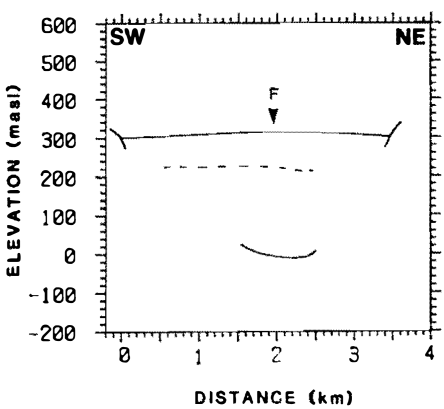

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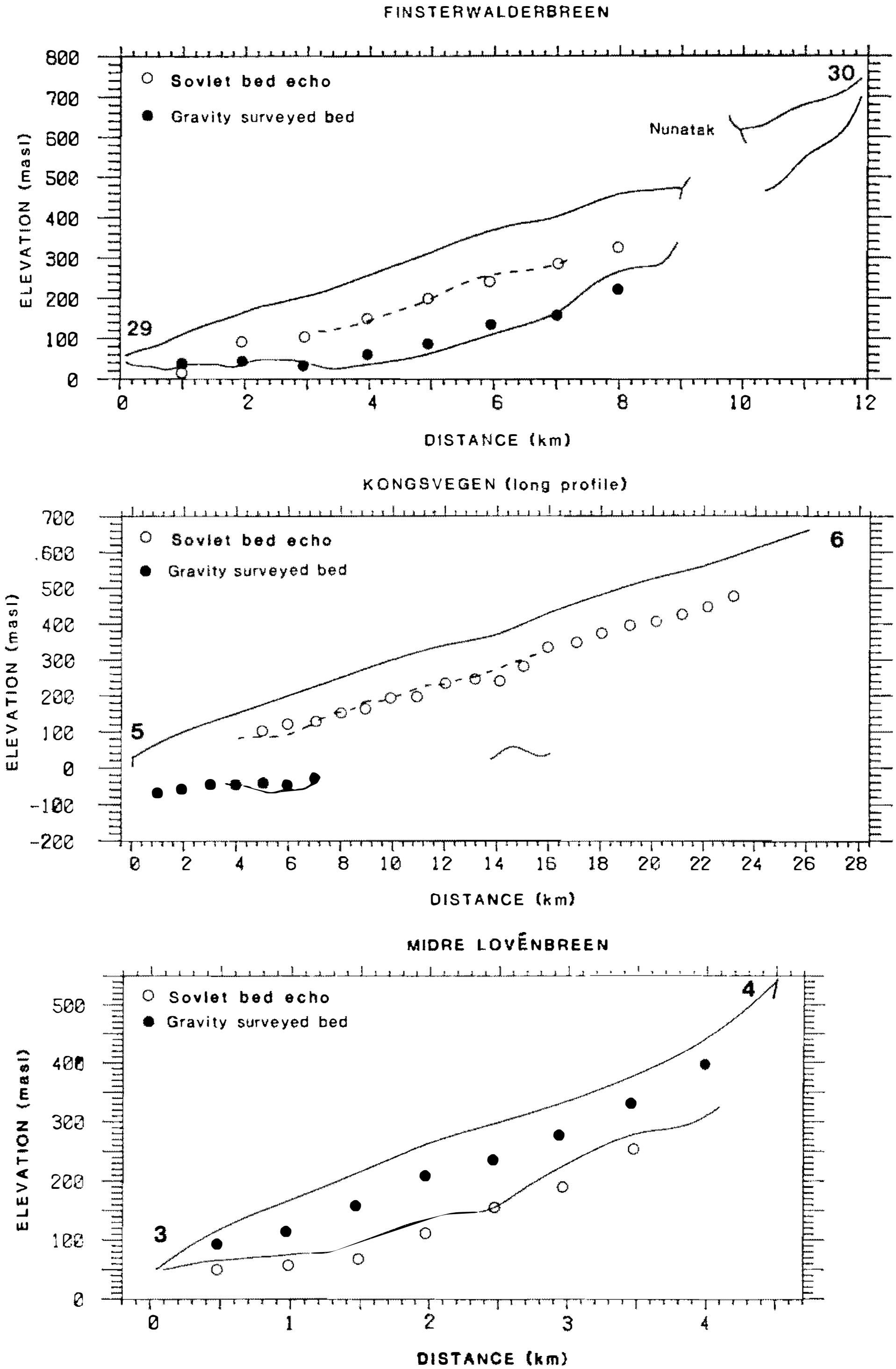


Fig. 16. – Long profiles of Finsterwalderbreen, Kongsvegen and Midre Lovénbreen, including the results of gravity surveys and Soviet radio echo sounding. Numbers locate the profiles in Figures 5 and 14.

sounded in 1980 for which borehole depth data were available. The 60 MHz system recorded bottom returns at 205 m in its vicinity. Soviet radio echo sounding data also agreed well with these thickness measurements.

Previous radio echo sounding

Apart from limited oversnow radar sounding on Foxfonna (Liestøl 1974), all previous echo sounding in Spitsbergen has been carried out by Soviet workers. On Austre Brøggerbreen, in particular, detailed oversnow traverses have been undertaken (Macheret & Zhuravlev 1982), but most Soviet data have been collected from the air using helicopter-mounted 440 and 620 MHz systems (Macharet & Zhuravlev 1980; Kotlyakov et al. 1982). Dowdeswell et al. (1984) have discussed the comparison of SPRI-NP and Soviet radio echo sounding. This and the following sections draw heavily on that publication.

Bed and internal layer echoes recorded by Soviet radar systems are shown in Figures 16 and 17. The glaciers Finsterwalderbreen, Kongsvegen, Negribreen, Hansbreen and Penckbreen all show significant differences in ice thickness relative to SPRI Mk. IV sounding during 1980. In each case Soviet data *underestimate* glacier depth, and are also considerably less thick than gravity surveys from Finsterwalderbreen and Kongsvegen.

There is also close correspondence between Soviet echoes assumed to represent the ice-bed interface and internal reflections recorded by the SPRI Mk. IV system (Figs. 16 and 17). However, in the lower part of Negribreen an internal echo is explicitly identified as such by Macheret & Zhuravlev (1982) and here 60 MHz and Soviet bottom echoes coincide (Fig. 17).

Preliminary results of SPRI Mk. IV radio echo sounding in Svalbard during April and May 1983 also show that the thickness of several additional glaciers has been underestimated considerably in Soviet studies. These glaciers include Borebreen, Eidembreen, Lilliehöökbreen, Monacobreen, Raudfjordbreen, Tunabreen, Uvêrsbreen and Wahlenbergbreen.

However, close agreement (± 15%) between Soviet data and results from 1980 exists for Austre Brøggerbreen, Midre Lovénbreen, Austre Grønfjordbreen, Fridtjovbreen, Vestre Torellbreen and Werenskioldbreen (Figs. 13, 16 and 18). On the three latter glaciers, which are also the thicker of the six, a layer echo is observed above the bottom echo on Soviet records.

Radio echo sounding of sub-polar glaciers

Measured 10 m temperatures on a number of Svalbard glaciers indicate that many are of 'sub-polar' thermal regime, with accumulation zone ice at or near its melting point and ablation area ice some degrees colder (e.g. Sverdrup 1935; Schytt 1964; Baranowski 1975). 'Sub-polar' and 'temperate' glacier ice, because of higher bulk-temperatures and the presence of numerous impurities, is both less homogeneous and more 'lossy' to electromagnetic energy than colder Antarctic and Greenland ice masses. At these higher temperatures scattering and absorption of radio waves increase relative to colder ice (Robin et al. 1969), making radio echo sounding of

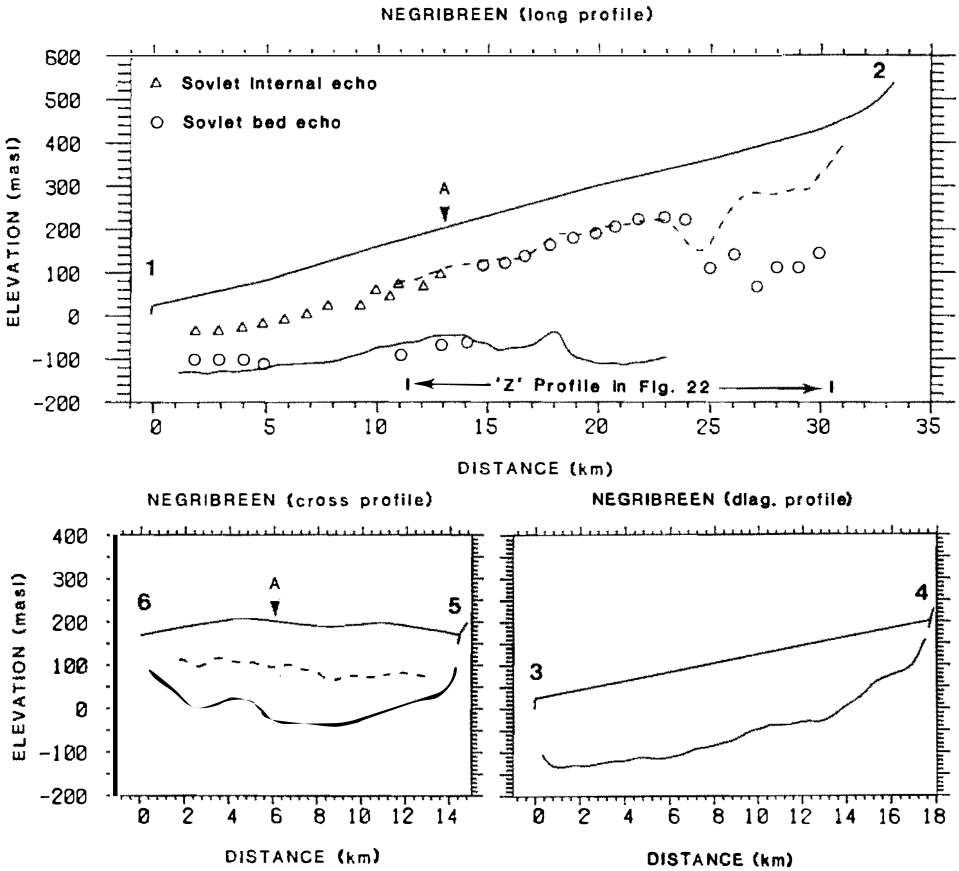
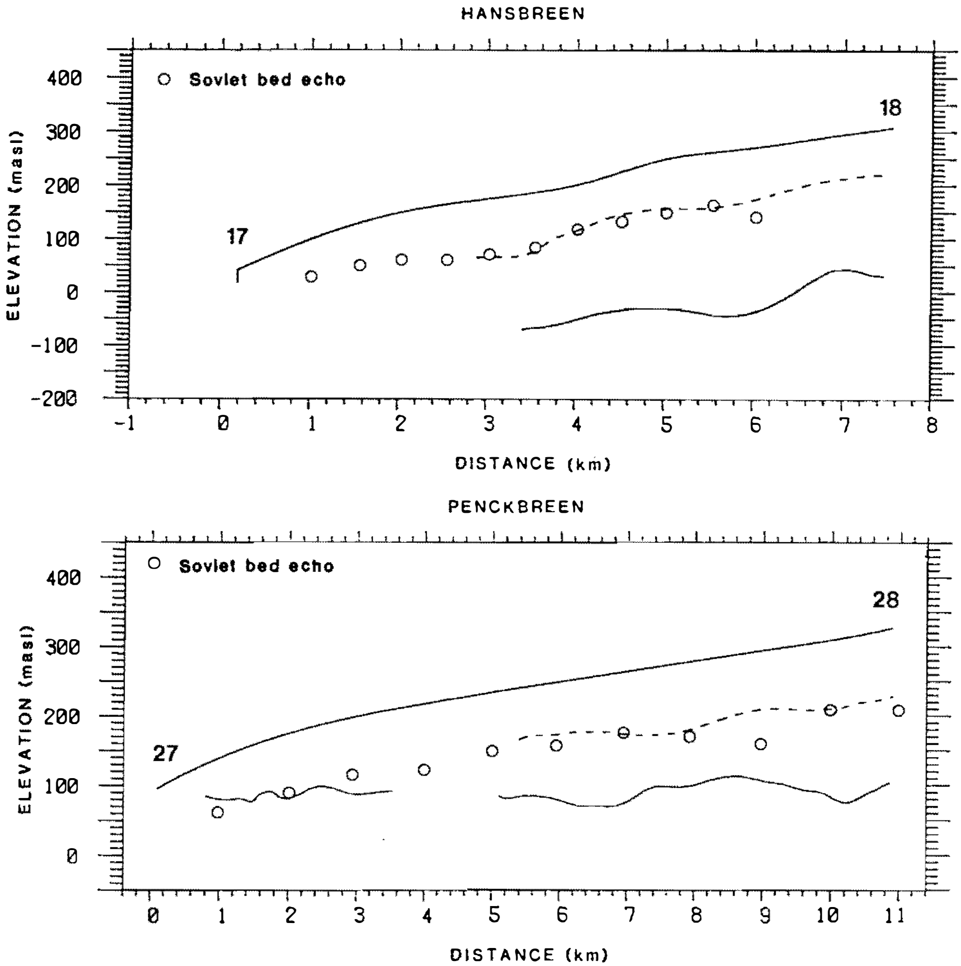


Fig. 17. – Long and cross profiles of Negribreen, Hansbreen and Penckbreen. Note the lack of correspondence between SPRI Mk. IV and Soviet radio echo sounding results. Numbers locate the profiles in Figures 5 and 8.

glacier thickness more difficult (Smith & Evans 1972; Goodman 1975; Watts & England 1976; Dowdeswell et al. 1984).

Smith & Evans (1972) pointed out that echoes from the base of glaciers near their melting point may remain undetected at the radar receiver for two principal reasons. First, radio waves can be *attenuated* by losses from both continuous and discrete inhomogeneities (e.g. water layers, ice lenses, water filled cavities) to a point where the returned signal is below the signal to noise ratio of the equipment. Increasing radar system performance will alleviate this problem. Second, the bottom return may be masked by the return from many discrete scatterers. In this situation it is the *ratio* between bottom echo signal and the returned power from a series of discrete scatterers that is important, rather than the power of the bottom return alone. The magnitude of this problem is dependent on radio wavelength and scatterer dimensions. Watts & England (1976) suggested that in this latter situation a reduction in radio frequency to below 10 MHz, thereby increasing radio wavelength relative to scatterer dimensions, provided a solution to the problem of masking of the bottom echo return. Miller (1979) and Sverrisson et al. (1980) have used a radar of this frequency in successful sounding of temperate glaciers in Iceland. However,



Goodman has also conducted successful trials with a 620 MHz sounder on temperate ice, finding that improved spatial resolution and lower sample volume compensated for increased signal attenuation.

Radio echo sounding of Spitsbergen glaciers at 60, 440 and 620 MHz

The system parameters of SPRI Mk. IV and Soviet 440 and 620 MHz radar equipment are compared in Table 5. The deepest ice sounded successfully by 620 MHz equipment was 540 m whereas the 440 MHz sounder had a maximum penetration of between only 150 and 250 m (Macheret 1981; Macheret & Zhuravlev 1982). The contrast in penetration between the two Soviet systems is due to the higher system performance and antenna gain of the 620 MHz equipment (Table 5). The SPRI Mk. IV sounder recorded a maximum ice thickness of 530 m on Holtedahlfonna during 1980.

The use of Soviet 440 MHz equipment to sound Svalbard glaciers more than 150–250 m thick could clearly lead to the misinterpretation of any continuous internal reflections as basal, since the true bed would be too deep to be recorded (Dowdeswell et al. 1984). This may explain the discrepancies between our own and

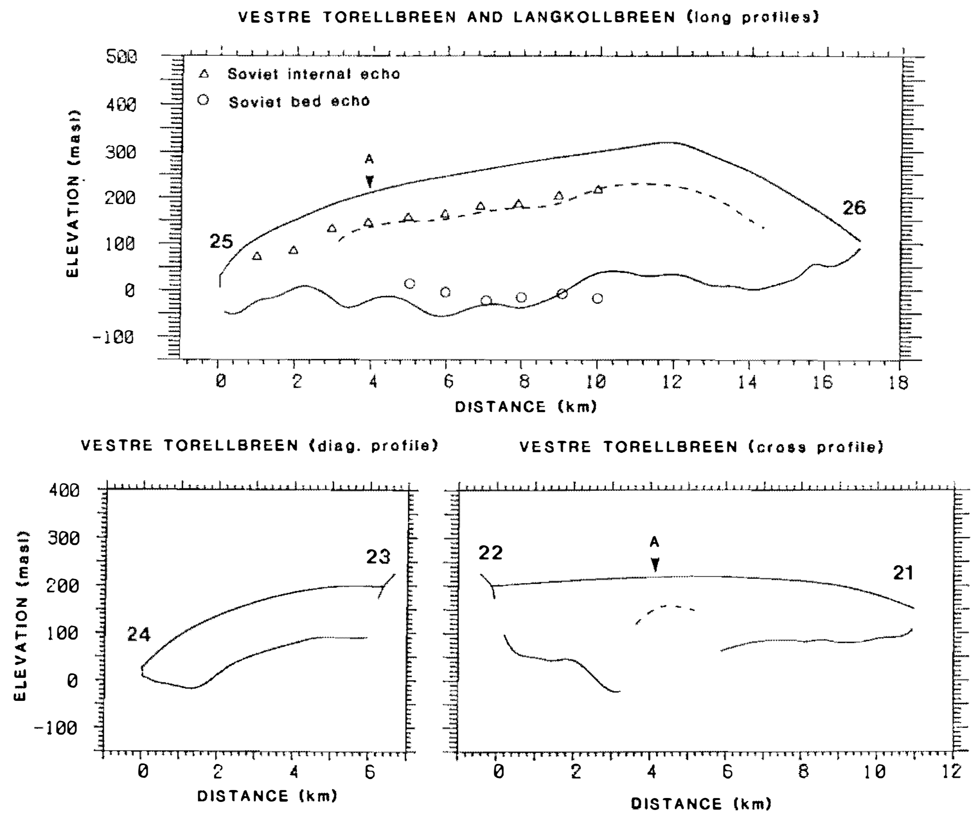
Table 5. Parameters of SPRI and Soviet radio echo sounding equipment used in Svalbard.

System	*Radio Echo Sounding Equipment*		
Parameter	*SPRI Mk. IV*	*RV-10,-17*	*RLS-620*
Transmitter power (W)	300	7	820
Carrier frequency (MHz) ...	60	440	620
Pulse length (ns)	300	500	100–1000
Receiver bandwidth (MHz)	15	6	15
System performance* (dB) ..	140	130	146
Antenna type	single $^1/_2$ wave dipole	two $^1/_2$ wave dipoles	16 element triple square grid
$^1/_2$ Power beamwidth (°)	100	100	18
Forward gain (dB)	2	2	19.5

* System performance excludes antenna gain, and a 20dB attenuation is included in the figure for the SPRI Mk. IV.

Soviet results from Finsterwalderbreen and Kongsvegen (Fig. 16), which were both sounded at 440 MHz during 1974 (Macheret 1976).

The reasons for discrepancies between the results of 60 and 620 MHz sounding are less obvious because the two systems penetrate to approximately similar maximum depths. However, although the Soviet equipment has a higher system performance and antenna gain than the SPRI Mk. IV radar (Table 5) a layer echo, rather than the true bed, was generally recorded during 620 MHz sounding of Negribreen, Hansbreen and Penckbreen (Fig. 17).



Smith & Evans (1972) showed that absorption and scattering by surface meltwater, soaked firn, ice layers and ice lenses increase with radio frequency. Their three layer model was used to calculate signal attenuation resulting from such inhomogeneities for a 250 m thick glacier at −2°C.

The model was used to compute the attenuation of electromagnetic waves at 60, 440 and 620 MHz on passing through: a) layers ofsoaked firn of varying density (Fig. 19); b) an ice layer located within firn of varying density (Fig. 20). Each figure shows the attenuation of em waves with increasing layer thickness. The systematic downward slope is a result of increasing absorption, and the oscillation is due to the reflection of em energy at the upper and lower boundaries of each layer in the model. The amplitude of oscillations increases as density differences between layers increase (Smith & Evans 1972). Values for attenuation represent one-way transit and should be doubled because each layer is traversed twice before the wave is detected at the radar receiver. The diagrams for each model show that attenuation rises rapidly with layer thickness as radio frequency increases (Figs. 19 and 20). Smith & Evans' (1972)

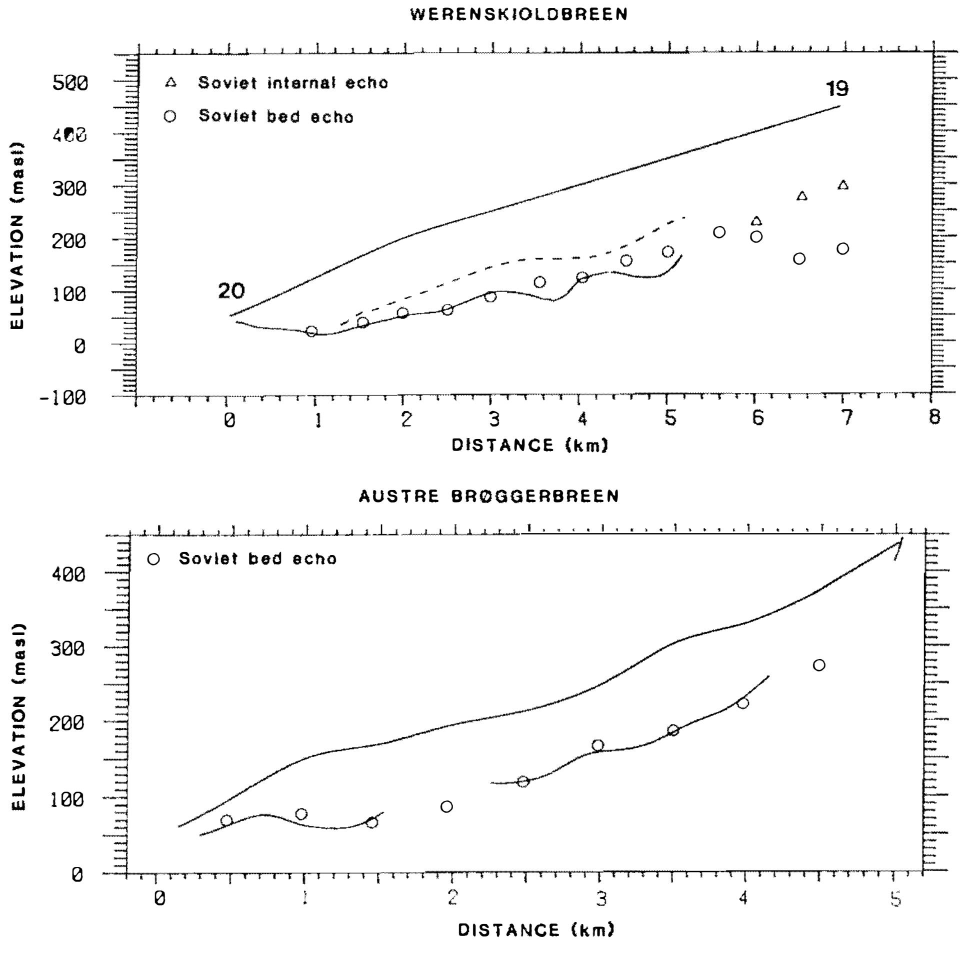


Fig. 18. – Profiles of Vestre Torellbreen, Werenskioldbreen and Austre Brøggerbreen. In this case ice thickness data from SPRI Mk. IV and Soviet equipment coincide relatively closely. Numbers locate the profiles in Figures 5 and 14.

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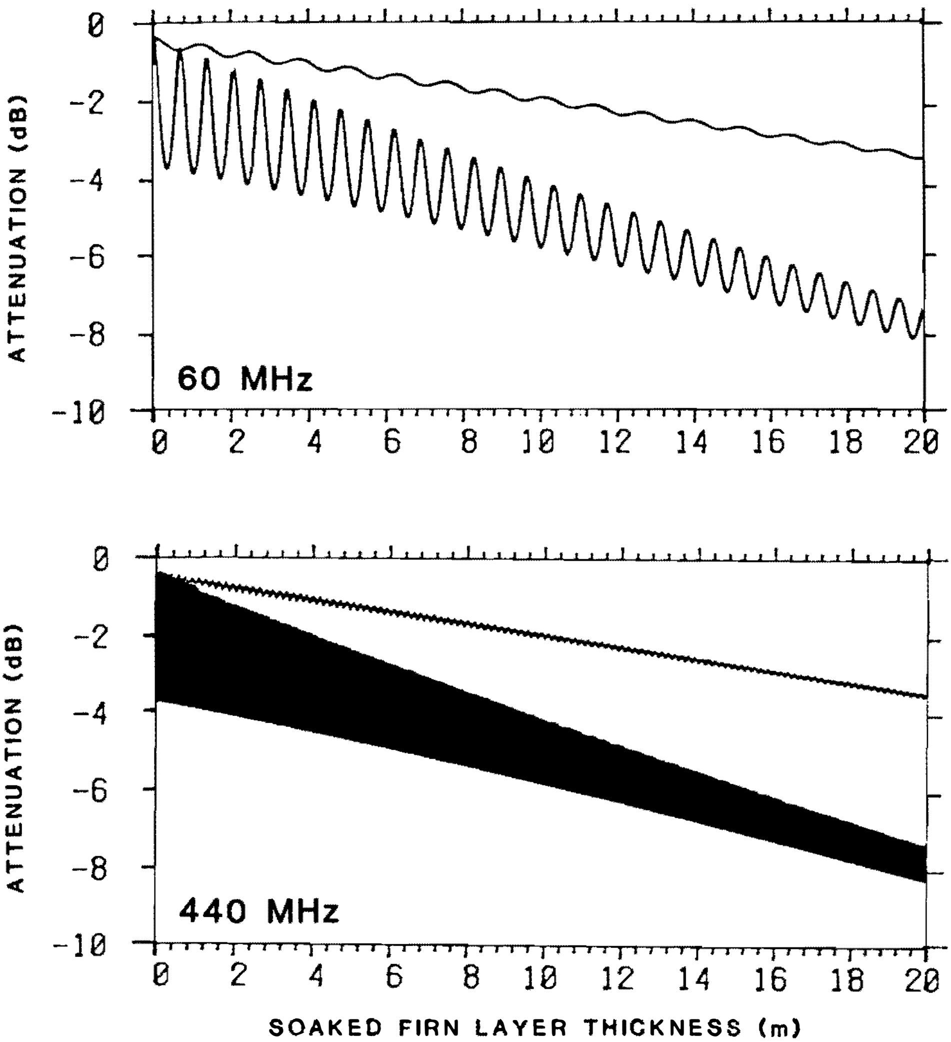

Fig. 19. – The attenuation of 60 and 440 MHz waves passing through firn with a rain-soaked layer (conductivity = $4 \times 10^{-3} \Omega^{-1}$ m^{-1}), as a function of layer thickness. The upper trace is for a firn density of 0.8 Mg m^{-3}, and the lower for a density of 0.5 Mg m^{-3}. 620 MHz data are not shown since oscillations are too closely spaced to reproduce at this scale. Calculations using the model of Smith & Evans (1972).

model also predicts that the presence of a 5 mm thick water layer on the glacier surface will result in two-way signal attenuation of about 1.5 dB at 60 MHz, but approximately 15 dB at 620 MHz.

Similar effects have been observed in the field. Davis et al. (1973), using a 440 MHz echo sounder, observed a 10 dB weakening of returned signals during daytime sounding of Roslin Gletscher, east Greenland, in the melt season. They suggested this might have resulted from the presence of a water layer some 5 mm in thickness.

In Spitsbergen, glacier surface water, soaked firn and ice layers and lenses are common phenomena. Liestøl et al. (1980) have described supraglacial lakes on several Spitsbergen glaciers during summer (Fig. 21), and thin layers of surface melt

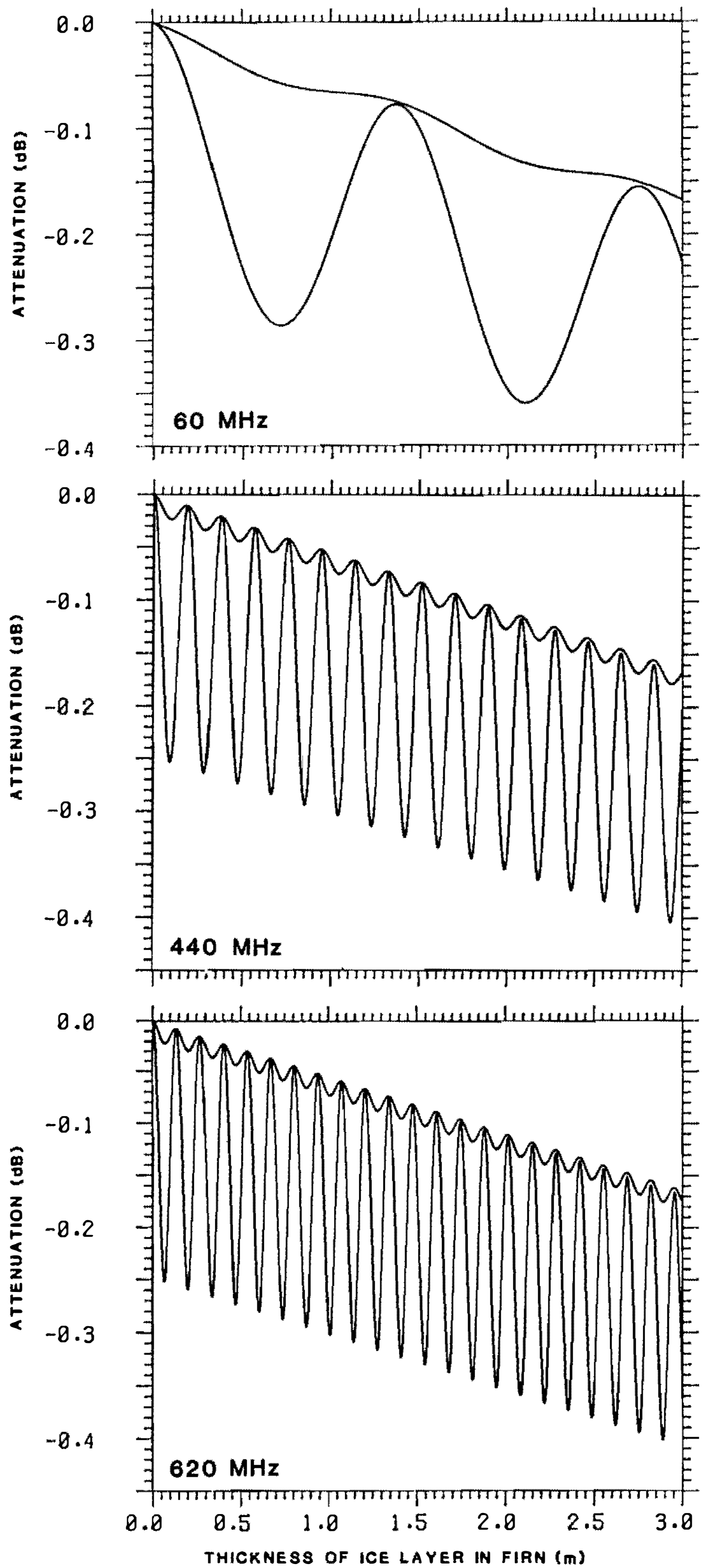

Fig. 20. – The attenuation of 60, 440 and 620 MHz waves passing through an ice layer (density = 0.92 Mg m^{-3}, conductivity = $6 \times 10^{-5} \Omega^{-1}$ m^{-1}) lying in a firn medium, as a function of layer thickness. The upper trace is in firn of density 0.8 Mg m^{-3}. Calculations using the model of Smith & Evans (1972).

Fig. 21. - Photograph of supraglacial lakes on Sefströmbreen (Fig. 14).

are often present. Layers of slush up to 0.5 m thick have also been observed covering large areas around the firn line on many Spitsbergen glaciers with relatively low surface slopes. On Lomonosovfonna a soaked firn layer up to 2 m thick has been noted (Kotlyakov et al. 1980). Ice layers and lenses have also been observed during snow stratigraphic studies in Svalbard (Ahlmann 1935; Schytt 1964). Ahlmann, for example, reported more than ten discrete ice layers of between a few millimeters and 0.5 m in thickness from several 5 m snow pits on Isachsenfonna.

The 1980 echo sounding with SPRI Mk. IV 60 MHz radar therefore had two principal advantages over Soviet 620 MHz equipment: it was conducted at a lower radio frequency, and flying took place before the start of the melt season. Both reduce the effects of absorption and scattering by inhomogeneities within and on the surface of Spitsbergen glaciers.

Table 6. Altitude at which bottom echoes disappear on certain Spitsbergen glaciers.

Glacier	*Elevation of echo loss (m asl)*
Doktorbreen	460
Kongsvegen	440
Nathorstbreen	350
Negribreen	340
Paulabreen	330
Von Postbreen	430
Werenskioldbreen	360

Radio echo sounding of glacier accumulation areas

Both SPRI Mk. IV and Soviet equipment recorded bed echo returns only intermittently. In particular, Macheret (1981) reported the disappearance of 440 and 620 MHz signals in glacier accumulation areas and near ice divides on thicker glaciers. Bed echoes were only seldom recorded in similar areas during sounding at 60 MHz. For example, bottom echoes were noted for less than 20% of a 109 km flight over Isachsenfonna and Holtedahlfonna (Table 4). Bottom returns also disappear in the accumulation areas of several glaciers (Table 6).

Measured 10 m temperatures on a number of Spitsbergen glaciers suggest that firn and ice in accumulation areas are often close to the pressure melting point (e.g. Sverdrup 1935; Baranowski 1975). The high temperatures, along with liquid water and inhomogeneities associated with melting and refreezing, may partly account for the lack of success of both our own and Soviet equipment in sounding the accumulation zones of thicker glaciers.

Smith & Evans (1972) reproduced several radio echo sounding records illustrating the masking of bottom echoes by diffuse returns from a multitude of scatterers. Similar 'Z' mode displays were recorded during 60 MHz sounding in 1980 (Fig. 22). The masking of bed echoes may occur preferentially in the accumulation areas of sub-polar glaciers as ice lenses are common in the firn and water inclusions and other discrete inhomogeneities are more numerous in firn and ice at its melting point.

The problems involved in radio echo sounding on sub-polar glaciers may, therefore, vary between the accumulation and ablation zones, and different strategies may be appropriate to obtaining an unambiguous bottom echo. In accumulation areas, where bottom returns are often obscured by scatter echoes, a reduction in radio frequency to below 10 MHz may be appropriate. However, the relative success of 60 MHz sounding at lower elevations on sub-polar Spitsbergen glaciers implies that an increase in the system performance of Soviet UHF equipment might lead to deeper penetration in glacier ablation areas since losses by absorption and scattering may be the principal problem here.

Finally, in the lower parts of glaciers masking of the bottom echo by scatter returns occurs where heavy surface crevassing is present (Figs. 9 and 10).

Internal reflecting horizons in Spitsbergen glaciers

Internal reflections from depths of 70–180 m were reported by Macheret & Zhuravlev (1980). Reflecting horizons were recorded at between 70 and 190 m by SPRI Mk. IV equipment, with about 70% of observations falling between 90 and 110 m depth (e.g. Figs. 16 and 17). These layers are different from multiples of the ice surface echo. Only single isolated layer echoes were observed on any glacier, although it is not known whether a reflection corresponds to a single discontinuity in the ice or is integrated over the pulse length or wavelength of the radar (Harrison 1973). The multiple layer echoes observed in the Antarctic and Greenland ice sheets have not been reported from radio echo sounding studies of Spitsbergen glaciers. Further, comparison between spring and summer sounding by our own and Soviet systems indicates that these isolated layers are relatively constant in location, in

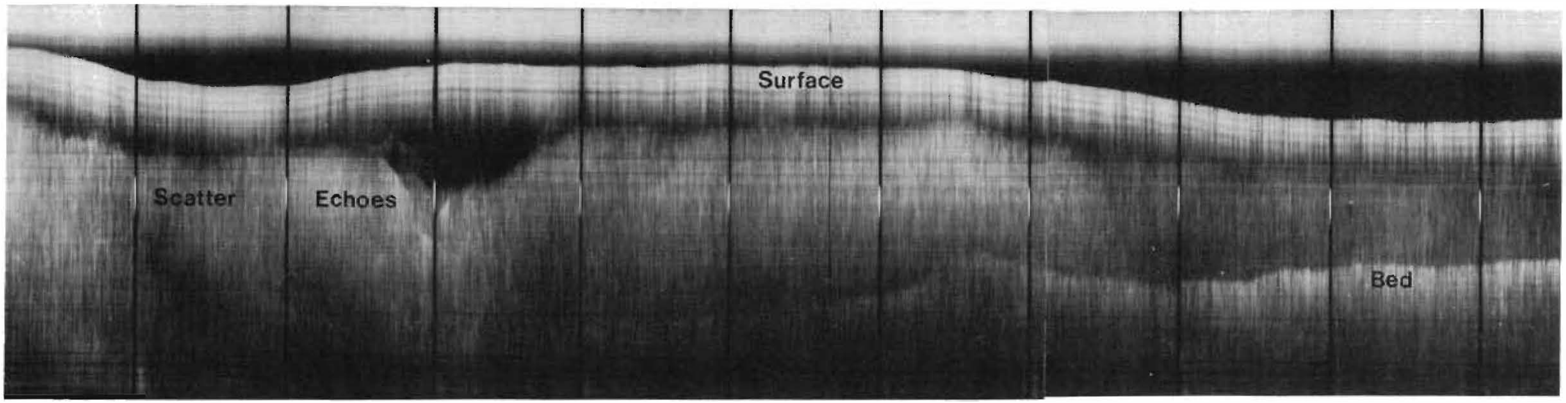

Fig. 22. – Bottom returns obscured by power scattered from many discrete reflectors in the accumulation area of Negribreen (Fig. 17).

contrast to the rapidly changing pattern of intraglacial reflectors interpreted as expressions of internal hydrological changes by Goodman (1973).

Internal reflectors could result from the presence of impurities (such as moraine or ash layers and chemical precipitates), fluctuations in ice density, bubble content, geometry and crystal axis orientation, the presence of brine, or changes in water content with depth.

Reflection coefficients cannot be used to estimate the possible causes of layer echoes because quantitative echo strength measurements were not made in 1980. However, from visual inspection bottom echo returns were usually stronger than layer signals (Fig. 3). This, along with the lack of an obvious debris source in many areas, indicates that the internal reflector is probably not a moraine layer. Ice cores from Fridtjovbreen (Fig. 13) did not reveal any moraine layers, but transparent and impure layers were noted within bubbly ice at depths of 50–85 m, 102–106 m and 145–149 m (Zagorodnov & Zotikov 1981; Macheret & Zhuravlev 1982). Macheret & Zhuravlev (1982) also reported preliminary ice core data suggesting that ice with a water content of 1–2% was present at depths greater than 115 m, which coincided with the height of the internal reflecting horizon at this point on the glacier. The layer echo might, therefore, be associated with ice at the pressure melting point. However, more ice core drilling, together with detailed radio echo sounding experiments (i.e. recording of signal strengths, reflection coefficients and polarization studies), are needed to provide additional evidence concerning the interpretation of these layer echoes.

Conclusions

Airborne radio echo sounding of Spitsbergen glaciers during 1980 provided 360 track km of the thickness data. Little previous glaciological information existed for many of these ice masses. Long and cross profiles were constructed for ice masses in four main areas of the island: southern Spitsbergen, Olav V Land, Nordenskiöld Land and north-western Spitsbergen. Several regionally specific problems were investigated. For example, the ice covered area between Sørkapp Land and the bulk of Spitsbergen was shown not to conceal a deep water trough. Reflecting horizons were also recorded within many glaciers. Deep drilling and additional radio echo sounding experiments are needed to establish the nature of these internal reflectors.

Good agreement (±10%) was found between ice thickness measured through 60 MHz radio echo sounding and independent borehole and gravity data. However, significant discrepancies were noted between the results of SPRI Mk. IV and Soviet UHF radar sounding. Where 60 MHz and UHF ice thickness measurements disagreed, Soviet results always indicated much thinner ice. This was often due to the misinterpretation of an internal layer echo as the glacier bed (Dowdeswell et al. 1984). Preliminary results of 60 MHz sounding during 1983 indicate that this problem may extend to a number of other glaciers in Spitsbergen. Problems with Soviet 440 MHz sounding were due to its relatively low system performance. Soviet 620 MHz radar did not always penetrate to the glacier bed because: (1) scattering and absorption increase significantly with radar frequency, and (2) sounding was conducted in summer when much meltwater was present to attenuate signal power.

In general, SPRI Mk. IV 60 MHz equipment yielded unambiguous bottom echoes over much of the lower parts of sub-polar Spitsbergen glaciers. This was despite a sub-optimal antenna configuration and a system performance below SPRI Mk. IV specifications (Evans & Smith 1969). Bed echoes were obscured by scattering where ice was heavily crevassed, often as a result of glacier surging.

In the accumulation zones of certain glaciers (Table 6), and on the larger ice masses of Holtedahlfonna and Isachsenfonna, bottom echoes were often masked by the returns from large numbers of scatterers. These inhomogeneities were present due to melting and refreezing associated with the relatively warm ice found in the accumulation areas of many Spitsbergen glaciers. The presence of returns from a multitude of scatterers is, therefore, a qualitative indicator of the presence of warm ice in glacier accumulation areas.

Acknowledgements

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