Radio Echo Sounding on Four Ice Caps in Arctic Canada

W. S. B. PATERSON and R. M. KOERNER[1]

ABSTRACT. An SCR 718 radar altimeter, mounted on a sledge towed by a motor toboggan, was used to measure ice thickness on parts of the Devon Island Ice Cap, the ice cap on northwestern Ellesmere Island, the Meighen Ice Cap, and the southernmost of the four ice caps on western Melville Island. No echoes were received where the ice thickness exceeded about 800 m. Techniques are described and results presented as bedrock contour maps. On Meighen Ice Cap results of soundings with two radars of different frequencies did not differ significantly but showed some discrepancies from the results of a gravity survey.

RÉSUMÉ. *Echosondages radio sur quatre calottes glaciaires du Canada arctique.* Les auteurs ont employé un altimètre radar SCR 718 monté sur un traîneau remorqué par une motoneige, pour mesurer l'épaisseur de la glace sur des portions de la calotte de l'île de Devon, de la calotte du nord-ouest de l'île d'Ellesmere, de la calotte de Meighen et de la plus méridionale des quatre calottes de l'ouest de l'île de Melville. Là où l'épaisseur de la glace dépasse 800 m, ils n'ont reçu aucun écho. Ils décrivent ici leurs techniques et présentent leurs résultats sous forme de cartes en courbes de niveau de la roche-mère. Sur la calotte de l'île de Meighen, les résultats de sondages effectués avec deux radars de fréquences différentes ne diffèrent pas de façon significative mais montrent des divergences par rapport aux résultats d'un levé gravimétrique.

РЕЗЮМЕ. *Зондирование четырех ледников на Крайнем Севере Канады методом радиоэхо.* Радиолокационный высотомер SCR 718, установленный на моторных санях, использовался для измерения мощности льда в различных частях о.Девон, в северо-западной части о.Элсмира, на о.Майген и на самом южном из четырех ледников на о.Мелвилл. При толщине льда более 800 м отражение сигналов зарегистрировать не удалось. Описана техника измерений и результаты представлены в виде контурных карт коренных пород. Результаты зондирования ледника на о.Майген двумя радарными установками, работающими на различных частотах, существенно не отличаются, но обнаруживаются некоторые несоответствия с результатами гравитационной съемки.

INTRODUCTION

In 1970, under the Polar Continental Shelf Project, ice thickness was measured by radio echo sounding on parts of the Devon Island Ice Cap, the large ice cap on northwestern Ellesmere Island, the Meighen Ice Cap, and the southernmost of the four ice caps on western Melville Island (Fig. 1). The objective on Devon and Ellesmere Islands was to find a site where ice thickness and bedrock topography were suitable for a deep borehole; on Meighen and Melville Islands the aim was to supplement information already obtained from gravity surveys (Hornal, 1961; Spector, 1966). In this paper the techniques are described and the results presented.

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[1]Polar Continental Shelf Project, Department of Energy, Mines and Resources, Ottawa, Ontario, Canada.

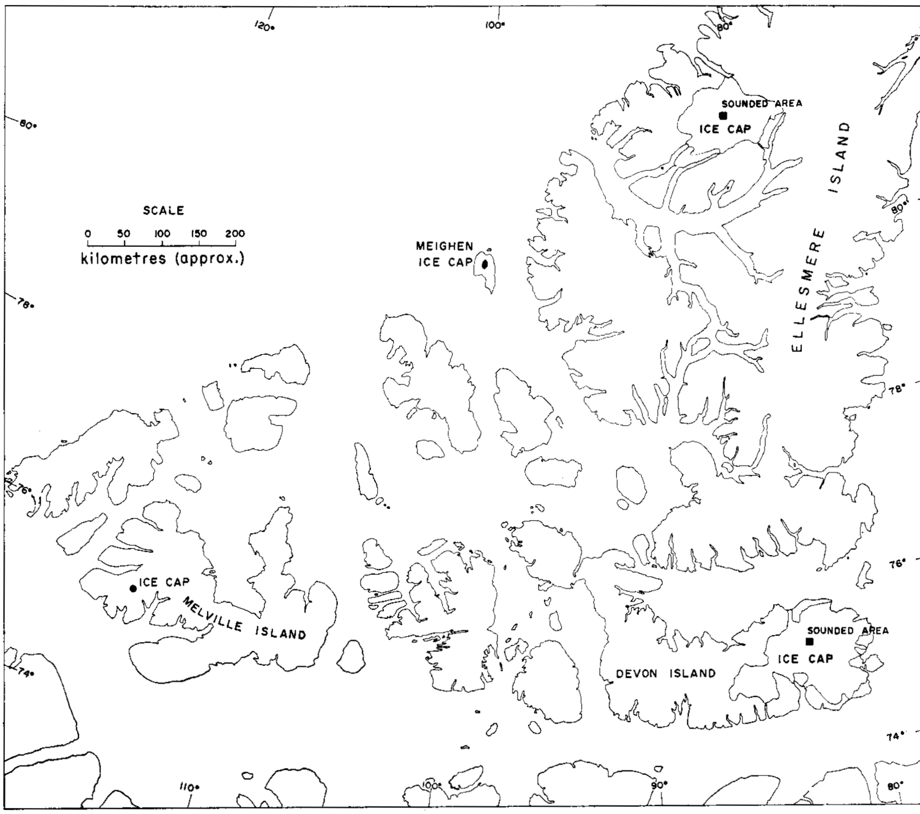

FIG. 1. Location of sounded areas. In Ellesmere Island, two areas were sounded but were too close together to be separated on this map.

TECHNIQUES

The equipment and methods were similar to those of Weber and Andrieux (1970) on the Penny Ice Cap, Baffin Island. An SCR 718 radar altimeter, on loan from the Canadian Armed Forces, was housed in a cabin on a Nansen sledge pulled by motor toboggan (Fig. 2). The dipole antennas, backed by aluminum sheets,

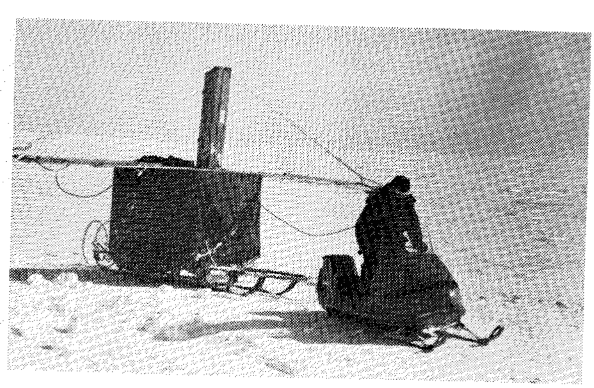

FIG. 2. Equipment used for radio echo sounding.

were mounted approximately 4 m. apart, one on either side of the cabin. Power was supplied by a 110-volt, 400 Hz. dynamotor driven from two 12-volt heavy-duty vehicle batteries which were recharged overnight after each day's soundings.

Most of the measurements consisted of spot soundings. An observer in the cabin watched the oscilloscope continuously, but the depth measurements were made when the vehicle was stationary. Contrary to the experience of Weber and Andrieux (1970), few reflections were observed from layers within the ice and there was no difficulty in distinguishing the bedrock reflection from them. Sometimes, when the vehicle stopped, the bedrock echo was weak, or split into two or three closely-spaced echoes of different strengths; but movement of the sledge by a distance of about 1 m. was usually sufficient to enable a single echo of adequate strength to be obtained. Bailey *et al.* (1964) have reported similar changes in echo strength over distances of the order of one radar wavelength. The changes occur because the bedrock has a rough surface and so the form of the reflected signal is determined by diffraction (Nye *et al.* 1972). Ice less than 60 m. thick could not be sounded because the reflected echo could not be separated from the transmitted pulse, even when the receiver gain was reduced.

In addition to the standard radar display, there was a continuously-recording system which enabled ice thickness to be displayed in relation to distance on a storage oscilloscope which was photographed at the end of the run. The image on the tube lasted for 10 or 15 minutes, in which time a distance of about 3 km. could be sounded. Fig. 3 is an example of this type of record. Unfortunately, the power consumption of this system was so high that the batteries were discharged in about an hour, and so it was seldom used.

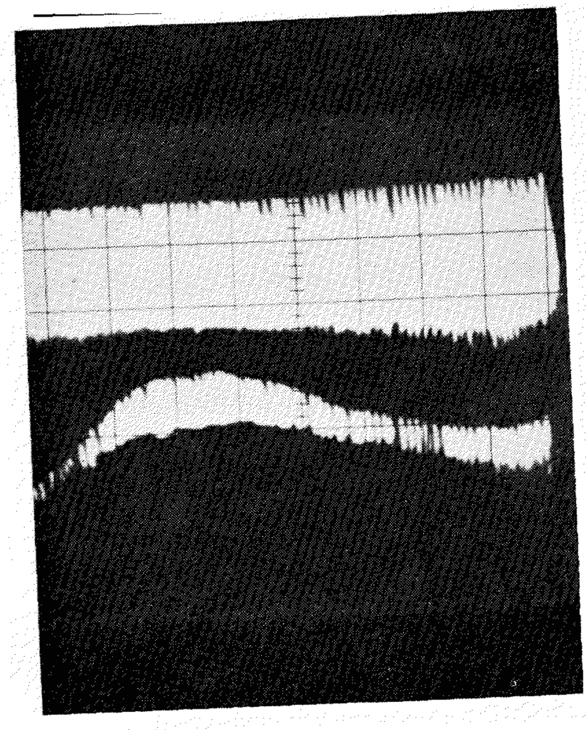

FIG. 3. Typical continuous sounding record from the Devon Island Ice Cap. The upper bright band is the transmitter pulse, the lower is the bedrock echo. Ice thickness is proportional to the distance between the upper edges of the two bands. Each vertical division corresponds to 109 m. of ice thickness; each horizontal division to a distance of 370 m. The record thus covers a distance of about 3 km with ice thicknesses between 300 and 500 m.

To adapt the scale readings on the normal radar display to the measurement of ice thickness, a relative permittivity of 3.17, corresponding to a velocity of radio waves in ice of 169 m./microsec., was used (Robin *et al.* 1969). This value produced the correct ice thickness at a 121 m. borehole through the Meighen Ice Cap. Because wave velocity depends on density, measured thicknesses should have been corrected to allow for the low-density snow and firn in the uppermost 50-60 m. of the ice caps on Devon and Ellesmere Islands. However the correction is only 8m. for the appropriate temperature ($-20°C$) (Robin *et al.* 1969), and as this is less than the margin of error in the reading (about 10 m.) it was ignored. This correction does not apply to the ice caps on Meighen and Melville Islands, because they consist entirely of ice. Subsequent to this work, two boreholes, about 25 m. apart, were drilled through the Devon Island Ice Cap. In both drillings bedrock was reached at 299 m. at a place where the radar indicated a thickness of 305 m. The measure of agreement was considered satisfactory. On Devon Island, echoes became weak where the ice thickness exceeded 700 m., and the maximum thickness from which an echo was obtained was 750 m. No echoes were obtained in the extreme south of the sounded area where the trend of the bedrock contours suggests that the ice thickness exceeds 750 m. On Ellesmere Island, on the other hand, thicknesses as great as 820 m. were measured. Ice temperatures were probably in the range $-15°C$ to $-25°C$ in both places.

Soundings were made at intervals of 250-300 m., occasionally supplemented by continuous profiles. On Meighen and Melville Islands, the sounding lines were related to the existing networks of stakes used for mass balance measurements. On Devon and Ellesmere Islands the lines were oriented by sun compass, and direction was maintained by sighting back on snow cairns or pieces of cardboard 15 cm. square. Distance was measured by a bicycle wheel attached to a sledge, and elevation by altimetry. On Devon Island, the sounding lines have subsequently been accurately surveyed using sun azimuth for absolute orientation, theodolite to measure angles where lines intersect or change direction, steel tape for distances, and levelling for relative elevations.

Bedrock elevation was determined from surface elevation and ice thickness; contour maps were then drawn by hand. In the cases of Devon and Ellesmere Islands, computer contouring was also tried using a modified general purpose contouring package on a CDC 6400 computer. For Devon Island, the results of the two methods differed only in minor details; on the other hand, for Ellesmere Island, where the bedrock topography is rougher than on Devon Island, the computer produced implausible results which could have been improved only by the use of a more sophisticated program.

RESULTS

Meighen Island

Soundings were made on the Meighen Ice Cap from 7-10 May. Because the SCR 718 radar altimeter cannot measure ice thicknesses of less than 60 m., no soundings were obtained in the northern third of the ice cap, in a band about 3 km. wide along with the western side, and in smaller bands on the east and south.

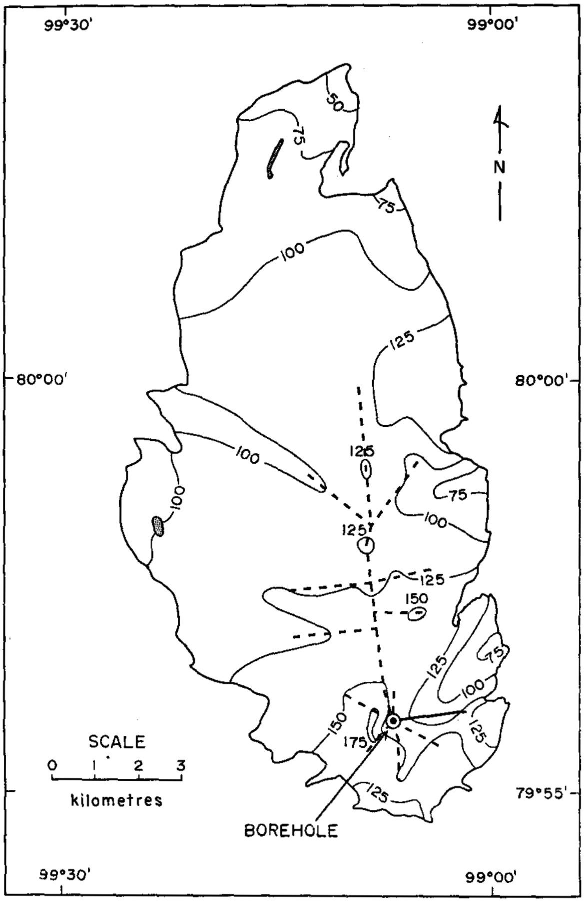

FIG. 4. Contour map of bedrock under the Meighen Ice Cap. Contours in metres above sea level. Spot soundings were made every 250 m. along the broken lines, and a continuous sounding along the solid line. Contours in other parts of the ice cap are based on a gravity survey, the elevation of nunataks, and the contours on land around the perimeter.

However, it proved possible to draw bedrock contours in the sounded area and to join these, in a consistent fashion, to the contours on the land around the perimeter, as shown on the detailed map (Meighen Ice Cap, Map 69H-560B (parts), scale 1:25,000, Surveys and Mapping Branch, Department of Mines and Technical Surveys, Ottawa, 1965). Fig. 4, where the results are shown, provides more detail of the bedrock under the thicker parts of the ice cap than do the bedrock contours on the map which were based on a gravity survey by Hornal (1961), a method that inevitably results in a smoothed picture of the underlying bedrock. Thicknesses measured by the two methods differ appreciably; in the central part of the ice cap, the radar method gives greater values than does the gravity method, whereas the reverse is the case in the southern part. Table 1 gives comparisons at a few representative points. Where thicknesses measured by the two methods differ, the radar values have been used to draw Fig. 4.

The work on Meighen Island also included a comparison of the SCR 718 radar altimeter (frequency 440 MHz.) with a Scott Polar Research Institute (SPRI) Mark II radio echo sounder (35 MHz.), operated by Dr. S. J. Jones of the Inland Waters Branch, Canadian Department of the Environment (Jones 1973). Table 1

TABLE 1. Comparison of measurements by two types of radar and by gravity survey

Station	Ice thickness (metres) measured by:		
	SPRI	SCR 718	gravity
20	97	102	74
21	106	107	80
24	97	98	74
25	106	108	88
Camp	107	120	92
27	106	117	91
29	<90	94	71
32	106	113	141
Borehole	121	121	142
34	101	113	123
35	<90	65	66

lists the soundings at all places where the two types of radar were used. The same value for the velocity of radio waves in ice (169 m./microsec.) was of course used in both cases. The SCR 718 appears to indicate consistently greater thicknesses; however, as each instrument can be read only with a precision of about 10 m., the mean difference of 6 m. is not important.

Attempts to obtain reflections from layers within the ice, for possible correlation with horizons in the core from the borehole, were unsuccessful.

Devon Island

Soundings were carried out between 14 and 19 May in an area of about 80 km.^{2} on the crest of the ice cap, about 7.5 km. west of the highest point. Fig. 5 is a bedrock contour map. The picture is one of flat-topped hills and deep valleys, with

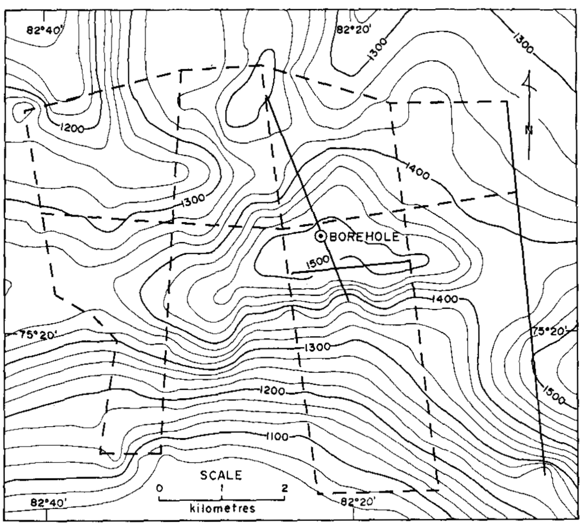

FIG. 5. Bedrock contour map of part of the Devon Island Ice Cap based on continuous soundings along the solid lines, and spot soundings about every 300 m. along the broken lines. Contours in metres above sea level. Absolute elevations may be in error by up to 50 m.

ice thicknesses from about 300 m. to more than 750 m. All the bedrock in this area is higher than any in the ice-free parts of Devon Island; elevations there do not exceed 1000 m. The crest of the ice cap in this region corresponds broadly to a bedrock high, as Hyndman (1965) found on a gravity traverse across the western part of the ice cap. This bedrock map, combined with the results of surface levelling and strain-rate measurements, is being used by one of the present authors (Paterson) in a detailed study of the relation between surface and bedrock topography.

Melville Island

Work on the southernmost of the four ice caps in western Melville Island was carried out between 27 May and 4 June. Much of the ice cap proved to be too shallow for effective sounding; the maximum thickness measured was 60 m. These results are reasonably consistent with those of the gravity survey by Spector (1966). His map shows a maximum thickness of about 50 m., but he predicted that thicker ice might be found in a narrow valley underlying part of the ice cap.

Ellesmere Island

Soundings were carried out between 15 and 21 June in two areas on the ice cap which lies northwest of Tanquary Fiord. The easternmost area (Fig. 6), which was surveyed first, is the highest part of the ice cap and consists of an ice divide where the surface slope is to the southeast and southwest. The bedrock topography is well dissected and dominated by an east-flowing valley for which there is very little surface expression.

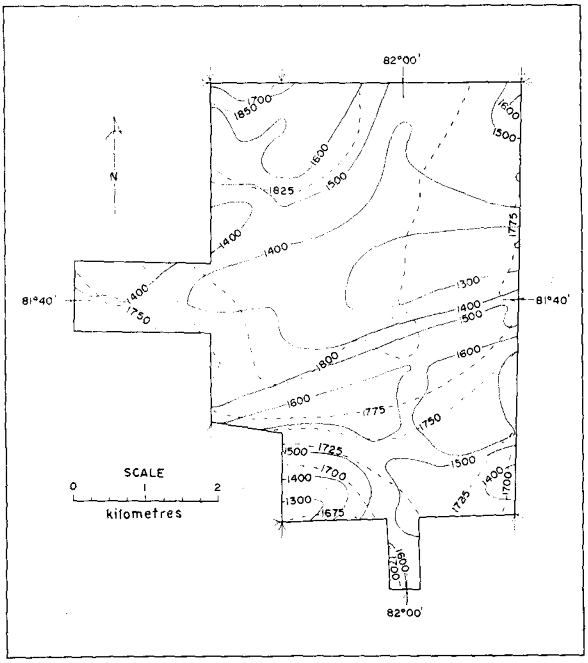

FIG. 6. Surface (broken lines) and bedrock (solid lines) contours, area A, northwest Ellesmere Island. Contours in metres above sea level, intervals 25 m. (surface) and 100 m. (bedrock). Absolute elevations may be in error by up to 50 m. Edges of map mark outside limits of survey. Arrows indicate ends of sounding lines.

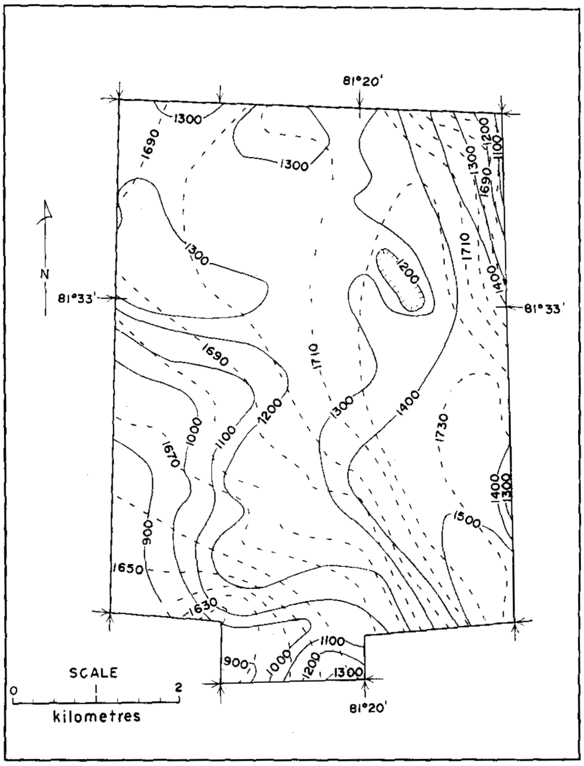

FIG. 7. Surface (broken lines) and bedrock (solid lines) contours, area B, northwest Ellesmere Island. Contours in metres above sea level, intervals 10 m. (surface) and 100 m. (bedrock). Absolute elevations may be in error by up to 50 m. Edges of map mark outside limits of survey. Arrows indicate ends of sounding lines.

The second area sounded (Fig. 7) is mainly on the western side of a north-south aligned ice divide and is part of the upper catchment area of the Otto Glacier. In this area thicknesses of 820 m. were measured despite reduced signal strength caused by an undetected fault in the antenna system. The soundings disclose a bedrock ridge which coincides fairly closely with one at the surface. A plateau on the northwestern part of the area and a deeply dissected valley in the southwest also show pronounced surface expression. There is a closed depression in the northeast, and this coincides with a small section where the network of sounding points is denser than elsewhere. An even finer sounding grid might show an opening to the depression. However, both areas that were sounded on Ellesmere Island may be more dissected than is shown, as the sounding grid was not fine enough.

ACKNOWLEDGMENTS

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